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Use of Ultrasonic Sensors on Mobile Cleaning Robots

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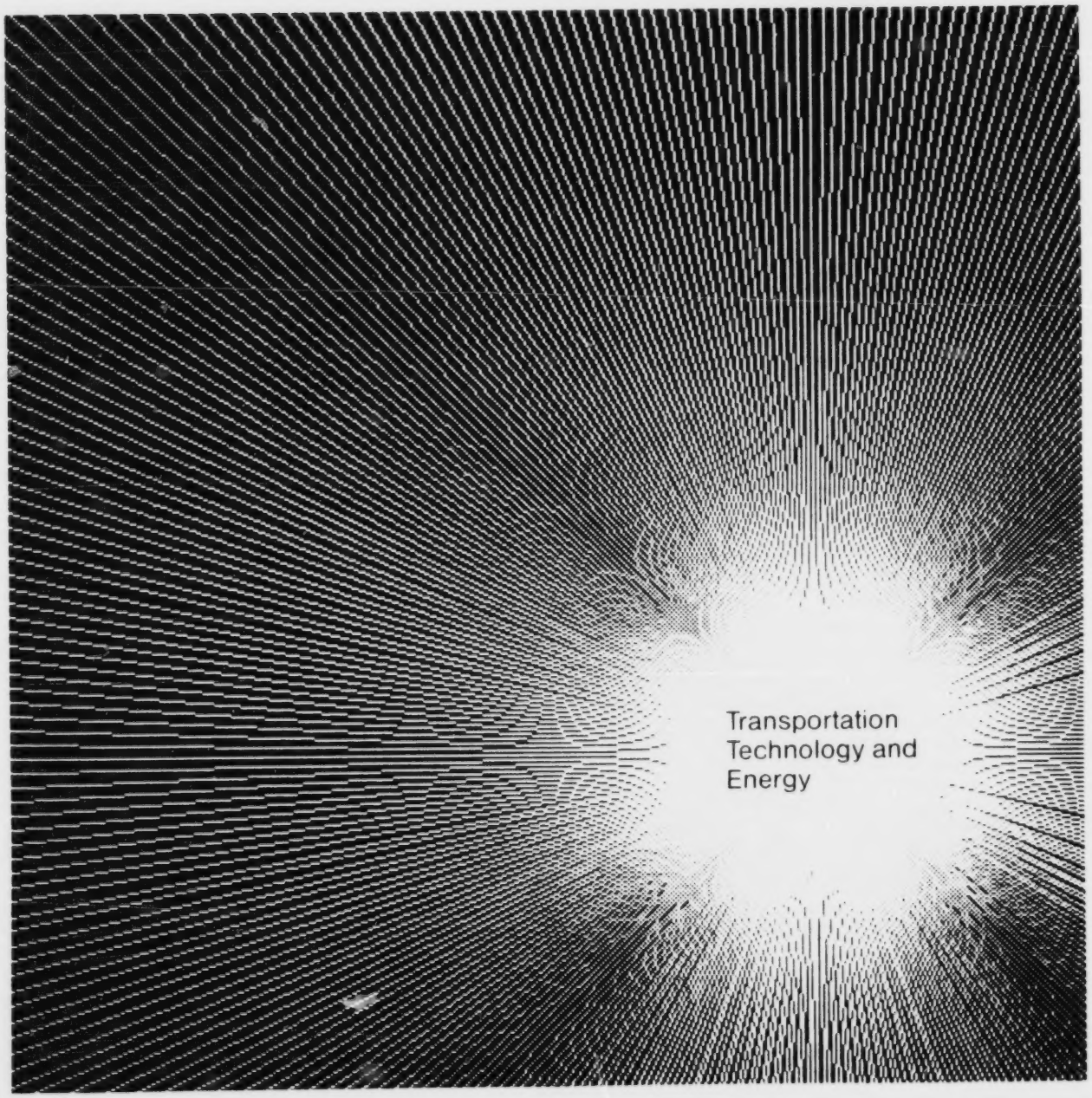

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Use of Ultrasonic Sensors on Mobile Cleaning Robots

Prepared by:	M. Hunter University of Waterloo Co-op Student
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Date:	April 1987
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Abstract:

A mobile robot project was established to design a completely autonomous vehicle to aid in the daily vacuuming and interior washing of transit vehicles, in particular, subway cars.

A major portion of this job includes the design of a guidance system. The primary task of this guidance system is to recognize the robot's location in the environment and its orientation with respect to its surroundings.

This report studies the technology and problems associated with using ultrasonics as the main component of the guidance system. It begins with a general project description and the reasons for choosing ultrasonics. An ultrasonic measuring device for a robot guidance system, using commercially available components, is discussed, along with various practical aspects of using ultrasonics for distance measurements. Tests are described as well.

Key words:	ultrasonic sensors, distance measurement, Polaroid, Texas Instruments, H5 subway car, sample rate, guidance system
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TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENTS	vi
EXECUTIVE SUMMARY	vii
1/INTRODUCTION	1
2/ GENERAL PROJECT DESCRIPTION	2
2.1/ Mobile Robot Project.	2
2.2/ Guidance System	2
2.3/ Choice of Ultrasonic Sensors.	3
3/ PRINCIPLE OF OPERATION	4
3.1/ How It Works.	4
3.2/ Typical Uses.	4
4/ DESIGN CONSIDERATIONS	5
4.1/ General	5
4.2/ Speed of Sound.	5
4.2.1/ Calibration Using Temperature-Sensing Devices.	6
4.2.2/ Calibration Using a Known Distance	6
4.3/ Beam Width	6
4.3.1/ Changing Beam Width.	6
4.3.2/ Testing.	7
4.4/ Positioning the Transducers	7
4.4.1/ Strategic Spacing.	7
4.4.2/ Beam Splitting	7
4.4.3/ Fixed vs Movable Sensors	7
4.4.4/ Height	8
4.5/ Range	8
4.5.1/ Maximum Range.	8
4.5.2/ Sample Rate.	9
4.5.3/ Minimum Range	9
4.6/ Resolution	10
4.6.1/ Clock Frequency	10
4.6.2/ Software Loops vs Hardware Circuits.	11
4.6.3/ An Example	11
4.7/ Reflecting Surfaces	12
4.7.1/ Surface Geometry	12
4.7.2/ Surface Composition.	12

TABLE OF CONTENTS (CONT'D)

	PAGE
4.8/ Speed	13
4.8.1/ Sample Rate.	13
4.8.2/ Single Sample	13
4.9/ Interference.	14
4.9.1/ Tests.	14
4.9.2/ Vibration	14
5/ EQUIPMENT ON THE MARKET	15
5.1/ Polaroid Ultrasonic Ranging System.	15
5.2/ Texas Instruments Sonar Ranging Module.	15
5.3/ Polaroid Transducer	16
5.4/ Comparison.	16
6/REQUIREMENTS OF THE GUIDANCE SYSTEM	17
6.1/ General Description	17
6.2/ Specific Requirements	17
6.2.1/ Number of Sonars	17
6.2.2/ Range.	17
6.2.3/ Resolution	18
6.2.4/ Temperature and Humidity	18
6.2.5/ Reflecting Surfaces.	18
6.3.6/ Ultrasonic Modules	19
6.3.7/ Processing	19
6.3.8/ Robot Speed.	20
6.3.9/ Noise and Vibration.	20
6.3/ Summary of Requirements	20
7/ DESIGN CONCEPT	21
8/ TESTS	22
8.1/ Lab Test Summary.	22
8.2/ Lab Test Conclusions.	22
8.3/ H5 Subway Car Test Summary.	23
8.4/ H5 Subway Car Test Conclusions.	23
9/ CONCLUSIONS AND RECOMMENDATIONS	25
10/ REFERENCES	26

TABLE OF CONTENTS (CONT'D)

PAGE

APPENDICES
A/ Test Section. 46
B/ Polaroid Transducer 123
C/ Polaroid Ultrasonic Unit. 127
D/ Texas Instruments Sonar Unit. 142

LIST OF FIGURES

	PAGE
1/ General Block Diagram	27
2/ Guidance System - Block Diagram	28
3/ A Typical Ultrasonic Module	29
4/ Beam Width.	30
5/ Coverage Area vs Distance	31
6/ Placement Patterns.	32
7/ Beam Splitting.	33
8/ Sample Rate vs Range.	34
9/ Transmission Time/Energy Decay Time vs Minimum Range.	36
10/ Resolution.	37
11/ Distortion by Complex Surfaces.	38
12/ Velocity vs Sample Time	39
13/ Sample Length	40
14/ Polaroid Ultrasonic Ranging System.	41
15/ Polaroid Timing Diagram and Circuitry	42
16/ Texas Instruments Sonar System.	43
17/ Timing Diagram - Texas Instruments.	44
18/ Guidance System Design Concept.	45
A1/ Experimental Setup (March 11)	50
A2/ Experimental Setup (March 17)	74
A3/ XMIT (March 19)	75
A4/ XMIT (March 19)	76
A5/ XMIT (March 19)	77
A6/ XMIT and MIC (March 20)	78
A7/ ECHO and MIC (March 20)	79
A8/ ECHO and MIC (March 20)	80
A9/ ECHO and MIC (March 20)	81
A10/ XMIT and INIT (March 24)	82
A11/ XMIT and INIT (March 24)	83
A12/ Experimental Setup - Addition of Buffers (March 24).	85
A13/ INIT and COUNT (March 24).	86
A14/ Experimental Setup - Separate Power Supplies (March 24).	90
A15/ INIT and COUNT (March 24).	91
A16/ ECHO (March 24).	92
A17/ H5 Subway Car Section.	121
A18/ Example of Sonar Readings in H5 Subway Car	122

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EXECUTIVE SUMMARY

A mobile robot project was established to design a completely autonomous vehicle to aid in the daily vacuuming and washing of transit vehicles, in particular, subway cars. A major portion of this job includes the design of a guidance system. The primary task of this guidance system is to recognize the robot's location in the environment and its orientation with respect to its surroundings. The properties of ultrasonics can be neatly applied to this problem.

This report studies the technology and problems associated with using ultrasonics as the main component of a guidance system. It shows that ultrasonic devices were chosen because of their non-contacting properties, cost, reliability, and current availability. It specifically recommends that the Texas Instruments sonar ranging module and the Polaroid instrument grade transducer be used.

The report begins with a general project description and the reasons for choosing ultrasonics. Many design considerations are then listed, and a detailed description on the principles and theory of ultrasonic ranging is given. A specific listing of requirements for the guidance system is given in Chapter 6 and then later justified.

Tests were conducted on the Texas Instruments module, both in the lab and in a subway car. It was concluded that the unit is fully capable of meeting most requirements. It was also noted that certain areas in a subway car, such as doors and some base sections, impose limitations on the use of the sonars. As well, interference was found to exist between adjacently placed transducers. All of these conditions, however, are easily overcome or insignificant. Thus, this report fully recommends using ultrasonic sensors as the basis of the guidance system for the mobile robot project.

Since this robot study (in the first part of 1986), further investigation of ultrasonics has been conducted for the purpose of building a device suitable for bridge height measurement at highway speed. This exercise increased the knowledge of ultrasonics, particularly in the areas of sensors' interference, high sampling rates, and influence of vehicle speed. This information is now being applied to the design of the robot's guidance system. The results will be published in a future report.

1/ INTRODUCTION

The applications of robotics are quickly expanding into many walks of society and industry. Of interest to the Ontario Ministry of Transportation and Communications (MTC) is the use ultrasonics to automatically measure the height of bridge underpasses while travelling at highway speeds. Another area in which there is increasing interest in progressing with this new technology is the maintenance of transit vehicles. With the use of robotics and automation, maintenance personnel can accomplish many unpleasant and tedious tasks both faster and at a higher rate of efficiency than in the past. The Ontario government is currently examining the application of a mobile robot for the daily cleaning of urban transit vehicles.

The essential component for the mobile robot is a guidance system. This guidance system must be a non-contact type of measuring system, which can be used without any modifications to the car. Choices for a non-contact system include tape, wire under the floor, markers, lasers, and ultrasonics. Ultrasonics is the most appropriate.

This report explores the use of an ultrasonic ranging module in the guidance system of the mobile robot.

Since this robot study (in the first part of 1986), further investigation of ultrasonics has been conducted for the purpose of building a device suitable for bridge height measurement at highway speed. This exercise increased the knowledge of ultrasonics, particularly in the areas of sensors' interference, high sampling rates, and influence of vehicle speed. This information is now being applied to the design of the robot's guidance system. The results will be published in a future report.

2/ GENERAL PROJECT DESCRIPTION

This section contains the general details of the mobile robot project and shows why a guidance system is needed. It elaborates on why an ultrasonic system was chosen over some other viable methods and also points out a few of the limitations associated with the choice.

2.1/ Mobile Robot Project

The interior cleaning of transit vehicles, specifically subway cars, is currently done manually in the Toronto area and most other parts of North America. The idea of a mobile robot to aid in the cleaning process is presently being examined by the Ministry of Transportation and Communications (MTC) within the Ontario government.

The purpose of the robot is to relieve the workers of the most mundane parts of the cleaning duty, decrease the cleaning time required, and perform a higher quality job.

A prototype model is currently being designed. It will be capable of vacuuming the floors of standard H5 subway cars, which are presently in use by the Toronto Transit Commission (TTC). In the future, it will become adaptable to other models of rail cars. The unit will be autonomous inside the subway car.

2.2/ Guidance System

A host computer (currently not decided upon) is expected to oversee the operation of the robot. Two other computer systems will aid in ensuring that the robot follows a selected path throughout the cleaning routine.

The first system, the control system, will supervise the motors for the drive wheels and cleaning arm. The system will execute commands sent from the host and will move the robot along a selected path.

A number of factors, however, illustrate why a second computer system is needed. When the host issues a series of commands to the control system, they are not always going to be executed to perfection. Mechanical slippage between the wheels and floor, transmission play, unforeseen objects in the subway car, and differences between each individual train car will cause errors in positioning. Thus, the second system, the guidance system, will track the actual position of the robot and inform the host computer of any deviations from the selected path. When a deviation occurs, the host will issue a new set of commands to the control system to correct the problem.

As shown in the block diagram of the system in Figure 1, the guidance system is an integral part of the robot and plays a key role in its navigation. Further examination reveals a need for a device to convey position information to a guidance computer. Several alternatives were examined.

2.3/ Choice of Ultrasonic Sensors

Before selection of the device, a few initial requirements were noted:

- A non-contact distance measuring system was desired. Information on the distance from the robot to its surroundings was needed, without any physical interaction with the environment.
- Due to the expense, it was desirable to make no alterations to the subway car.
- Parts must be relatively cheap and reliable.
- Parts should be readily available.

Several options were considered:

- Detection strips placed on the floor of the subway car for the robot to follow presented a simple way of ensuring that the robot was always in a known place about the subway car. A major drawback, however, is the above average wear and tear experienced by detection strips on a transit vehicle floor.

- A magnetic field along a buried cable has all of the advantages mentioned with the detection strip method and also solves the wear problem. This method, however, would require expensive modifications of the subway cars.

- Successfully used with mobile robots in the past, ultrasonic sensors are readily available, cheap, and give an accurate non-contact distance measurement. Drawbacks include a limited operating range, sensitivity to environmental conditions such as temperature and humidity, and problems with various forms of interference. The limitations imposed by the ultrasonic method, however, prove to be the easiest to overcome. The operating range is not a problem inside the small confines of a subway car. Temperature compensation methods exist, and interference sources, once identified, can be eliminated or allowed for in the design. Thus, for the guidance system, ultrasonic sensors were chosen to inform a guidance computer of the robots surroundings. Figure 2 further illustrates this idea.

3/ PRINCIPLE OF OPERATION

This section outlines how ultrasound can be used to make a non-contact distance measurement. The basic theory is discussed, and a variety of different applications are examined.

3.1/ How It Works

Ultrasound is simply a name for high-frequency sound waves. The frequencies used by the devices examined in this report are around 50 kHz.

Ultrasound can be used to make a measurement of distance in the following manner. The high-frequency sound waves are transmitted toward a target, and the resulting echo is detected. The elapsed time between transmission and echo detection can be used to calculate the distance if the speed of sound is known. For example, take the speed of sound to be 340 m/s. For a transmitted pulse to leave the transmitter, strike a target 1 m away, and return requires an average elapsed time of 5.88 ms.

An ultrasonic measuring device will have two major components: a transducer and a small circuit board. The transducer is a device that can transmit and receive ultrasound. Similar to a loudspeaker, it takes electrical energy and transforms it into sound waves when transmitting. As a receiver, it is capable of converting the echo back into electrical energy. An ultrasonic measuring system may incorporate two devices, one to transmit and another to receive, or may simply use one to do both tasks.

3.2/ Typical Uses

The advantage of using ultrasound to make a distance measurement is that no physical contact with the target is necessary. Difficult distances, such as from the roof of a moving car to the underside of a bridge, become simple measurements using ultrasound. As well, liquid levels in large tanks can be measured, distances in hazardous environments can be made, and object detection schemes devised.

In robotics, the properties of ultrasound may be used to measure distances to a surrounding environment and for object and intruder detection.

4/ DESIGN CONSIDERATIONS

In designing a system that incorporates ultrasonic devices, it becomes necessary to study and consider some important concepts. This section begins with a description of a typical ultrasonic measuring device and then individually examines the many factors governing its operation.

4.1/ General

Figure 3 illustrates a typical off-the-shelf ultrasonic ranging module and a timing diagram. The ultrasonic module is shown with its connected transducer. It requires power and a few support signals.

To initiate a measurement, INIT is brought to 5 V. The transducer will then send out a series of pulses at 50 kHz. After the energy of the transmission has died off, the transducer begins to act as a receiver and listens for the echo. Once detected, the module raises the signal ECHO to 5 V. The elapsed time between INIT being raised and ECHO going high is thus proportional to the distance to the target. Finally, INIT is brought low, ECHO will go low, and the current cycle lasts until INIT is raised again.

For the mobile robot project, a successful guidance system will have to link up to this module, initiate the measurement, begin timing until the echo is detected, perform calculations and conversions, and then communicate the information to the host computer (Figure 2).

4.2/ Speed of Sound

At 20°C, the speed of sound is 343.2 m/s. It varies only slightly with humidity, pressure, and frequency. Temperature variations are the major influence [1]:

- 331.3 m/s at 0°C
- 354.7 m/s at 40°C

a 7% variation.

Thus, distance readings from an ultrasonic unit will change considerably with temperature. To combat this problem, various compensation methods exist. They range from directly measuring the temperature, using a temperature-sensing circuit, to calibrating a measurement, based on taking a reading of a known distance.

On the mobile robot, some form of temperature compensation will be needed. Two methods are briefly discussed and referenced.

4.2.1/ Calibration Using Temperature-Sensing Devices

Temperature-sensing devices, such as the remote temperature sensor RTS-1 by Industrial Computer Designs, produce an output voltage that varies between two values over a set temperature range. With the use of an analog-to-digital converter, actual temperature information could be interfaced to a guidance computer to generate a correction factor [2,3].

4.2.2/ Calibration Using a Known Distance

Another method of correction is to take a measurement (D') of a known distance (D). Later, when a measurement (X') of an unknown distance (X) is performed, the actual distance X is simply calculated as $X = X' \cdot D/D'$. Thus, a true measurement can always be obtained as long as the environmental conditions remain the same as those present when the reading of D' was taken [4].

4.3/ Beam Width

Ultrasonic transducers emit a sound signal that progresses out towards the target in the shape of a conical beam (Figure 4).

The angle that this beam disperses at is important. If the beam width is too large, objects surrounding the target could return the echo. If the beam width is too small, however, a target could be missed completely. For example, a beam width of 30° will cover a circular area 53.5 cm in diameter at a range of 1 m. If the beam angle were only 8°, the coverage would be a circular area only 4 cm in diameter at the same 1 m. The further away from a target, the more area a fixed beam will cover. Figure 5 varies the parameters involved to illustrate this point.

4.3.1/ Changing Beam Width

A number of methods are available to modify the beam width emitted from a transducer. Beam width can be changed by altering the diameter of the transducer, using acoustical horns and lenses, and by varying the transmitting frequency (Figure 4).

The easiest way to alter the beam width is to use an acoustical horn or lense. The other methods require changes to be made in either transducer design or in the ultrasonic circuit board. Horns and lenses, however, can be cheaply made and tailored to fit a wide variety of transducers.

4.3.2/ Testing

Tests were done on the Polaroid instrument grade transducer. It has a specified beam width of 20° and was measured in the lab to be 19.7°. Experiments were also done with acoustical horns. It was found that by adding a 134 mm horn to the transducer, the beam width was decreased to 10.2° (Appendix A).

4.4/ Positioning the Transducers

To correctly position a transducer with respect to its target, knowledge of the beam width and the operating environment is important. Knowing this, the following can be useful.

4.4.1/ Strategic Spacing

Figure 6 illustrates how the correct spacing of two adjacent sonars is important. This example shows a mobile cart with six sensors positioned around it. Suppose it is using the sonars to guide it along the wall. If sonar B begins to give false readings due to a complex reflecting surface, range finder A can still be used because it continues to reflect off a good surface.

Similar surfaces exist inside subway cars. For the mobile robot, the farther apart the sensors, the better the chances to overcome these obstructions.

4.4.2/ Beam Splitting

Beam splitting involves using two or more sonars with overlapping beam patterns (Figure 7). If a target is detected by both sensors, then it must lie in the region of overlap. If it is detected by one range finder and not the other, then it must be in the small region exclusive to that sensor.

The advantage of beam splitting is that it reduces the uncertainty of target location within a beam. Drawbacks are that it requires two carefully placed sonars and more complex software to interpret the data.

4.4.3/ Fixed vs Movable Sensors

When considering placement of the transducers, their mobility should be considered. Placing a sonar on a motor-driven swivel would increase coverage area and the amount of information that each sensor could produce. The collection of the data, however, would be slower; motors and

control circuitry would then be needed; and the software requirements of the microprocessor unit (MPU) would drastically increase.

4.4.4/ Height

The height that the transducers are positioned at will be determined mainly by the environment. To determine placement on the robot cart, a careful examination of a subway car and the robot platform itself must be done.

Consider the environment of a TTC H5 subway car:

- At the base level, 0 to 27.5 cm above the floor, there are few obstructions, and the reflecting surfaces are good, being predominantly flat metal grids. At this level, however, exposure to dirt is the greatest, and the floor could interfere with a wide beam.
- At the seat level, 27.5 to 99 cm above the floor, many surface indentations exist because of the seats and dividers, and many poles begin at this level. Surfaces are mostly plastic and metal.
- At the window level, 99 cm and up, the surfaces are mostly glass, and there are few obstructions.

It must be determined which surfaces would offer the most useful information. This appears to be either the base level or window level since both are simple, relatively free of obstructions and have good reflective characteristics. Examining the robot cart, the base level offers the most room for locating the sonars, but suffers because the front vacuum arm could cause interference. At the window level, there is no current mounting for sonars. Thus, the base level appears the most likely height to place the sensors if the problem with the arm can be overcome.

4.5/ Range

The ultrasonic units tested each have a maximum and minimum operating range. A number of factors determine this range.

4.5.1/ Maximum Range

The farther the sound must travel through air, the weaker the reflected echo. All ultrasonic units will have a limit as to how weak an echo they will listen for. Most will stop listening after a preselected number of milliseconds.

Outside of this limitation, the sample rate will determine the maximum range of a module.

4.5.2/ Sample Rate

The sample rate is the number of times that a measurement is taken during each second. The faster the rate, the more measurements per second that occur and the less time allowed for the sound waves to travel to the target and back.

For example, consider the unit mentioned in Section 4.1. Assume a sample rate of five measurements per second. Each cycle has 200 ms. INIT must go high and then low again during this time. The measurement is over as soon as INIT goes low. It is the time when INIT is high that determines the maximum range. If INIT were high for 150 ms out of the 200 ms cycle, then the maximum range would be

$$\frac{340 \text{ m/s} \times 0.150 \text{ s}}{2} = 25.5 \text{ m}$$

using 340 m/s for the speed of sound. If the sample rate were increased to 100 times per second, each cycle would be only 10 ms long. Suppose INIT were high for only 5 ms of this. Then the maximum range would reduce to about

$$\frac{340 \text{ m/s} \times 0.005 \text{ s}}{2} = 0.85 \text{ m}$$

This is illustrated in Figure 8.

If a maximum range of 1.5 m were desired, then INIT would have to stay high for at least

$$\frac{2 \times 1.5 \text{ m}}{340 \text{ m/s}} = 0.0088 \text{ s} = 8.8 \text{ ms}$$

and the cycle time would have to be slightly larger, say 10 ms, to allow for INIT to go low and complete the process. Similarly, a desired range of 3 m would require a cycle time of almost 20 ms, or 50 times a second.

4.5.3/ Minimum Range

The minimum range is determined by the transducer type, transmission time, and transmission energy.

4.5.3.1/ Transducer Type

If the device is used as both a transmitter and a receiver, as is the Polaroid instrument grade model, then it will not be able to receive during the transmission. If a target is close enough, an echo could return and not be received because the transmission would still be in progress. The advantage with this type of model, however, is the simplified circuitry involved and reduced hardware.

If a separate receiver and transmitter are used, there will be no minimum range, since echo detection could begin as soon as the transmission started. This, however, would require an increase in circuit complexity.

4.5.3.2/ Duration of Transmission and Energy Decay Time

When a single device is used, it does not become a receiver until two things happen. First, a series of ultrasonic pulses are transmitted, and second, the energy in the transducer decays to a level such that a return echo can be detected. This total time defines the minimum range and is shown in Figure 9.

4.6/ Resolution

Resolution is the smallest change that can be accurately sensed. The resolution is determined by the frequency of the timer circuit used (Figure 10).

4.6.1/ Clock Frequency

When the ultrasonic tone is transmitted, a timing circuit must be started the instant the first signal leaves the transducer. As soon as the echo returns, the timer must stop, and its recorded value can then be converted into a distance.

Several options are open to the designer. This timing may be implemented in the MPU software as a repeating loop or in a separate hardware circuit which simply counts pulses from an oscillator. For a multi-channel system, however, the loop method is not possible because of speed considerations.

The frequency of the oscillator or software loop will determine how close the system can resolve distances. For example, consider a loop or clock of 20 kHz. Each cycle is 50 μs long. At the speed of sound, this represents about 17 mm or, considering that the sound must travel to the object and back, a distance of 8.5 mm to the target. Thus, with 20 kHz, a resolution of 8.5 mm would be obtainable. In contrast, a clock of

1 MHz gives a cycle time of only 1 μs. This translates to a distance of 0.17 mm to the target and produces a 0.17 mm resolution. Clearly, as the frequency increases, the finer the resolution gets.

If a resolution of 1 mm is desired, then the frequency needed in the software loop, or timer circuit, can easily be calculated as follows. For each resolution of 1 mm, the sound will have to travel 2 mm (to the target and back). This will take

$$340 \text{ m/s} \times Y \text{ s} = 0.002 \text{ m} = 2 \text{ mm}$$
$$Y = 0.002/340 = 5.9 \text{ μs}$$

This corresponds to a frequency of 1/5.9 μs = 170 kHz. Thus, the software loop or hardware counter circuit will need to cycle at least at 170 kHz to achieve a resolution of 1 mm.

4.6.2/ Software Loops vs Hardware Circuits

Both of these methods have their advantages. The software loop reduces the necessary circuitry and eliminates the problems of interfacing a hardware design to the guidance MPU. As well, software is more flexible because it can be more easily changed. A hardware design excels in its simplicity. The desired resolution will determine which is used.

Consider implementing a software loop in the guidance system's MPU to record echo times. High resolutions become difficult to obtain by this method. If the 1 mm resolution is desired, the loop will have to cycle each 5.9 μs. Even in a fast microprocessor, however, single instructions can take 3 or 4 μs, making it impossible to construct such a loop, since it will likely need several instructions. Thus, only when less precise resolutions can be tolerated should this method be considered.

4.6.3/ An Example

To conclude this section, another example is calculated. Consider the problem of determining what size counter to use if the hardware approach is used. Assume that only a 200 kHz oscillating circuit is available and that a maximum range of 3 m is desired.

1/ Calculate the resolution.
Each cycle is 1/200 kHz = 5×10^{-6} s = 5 μs
Sound will travel 340 m/s x 5 μs = 0.0017 m/cycle.

Thus, the distance to the target, per count, will be half of this, or 0.85 mm.

2/ Decide on a counter size.
The count multiplied by 0.85 mm will be the distance to the target.

Consider a 12-bit binary counter. The maximum count would be $2^{12} - 1$ or 4095. This value multiplied by 0.85 mm is 3480.75 mm, which is the distance to the target. This is about 3.5 m and corresponds to the maximum range. Thus, a 12-bit counter at 200 kHz could give a resolution of 0.85 mm and permit about a 3.5 m maximum range.

4.7/ Reflecting Surfaces

Two factors relating to objects reflecting ultrasound should be examined. They are the target's surface geometry and its composition.

4.7.1/ Surface Geometry

The surface geometry of reflecting objects can influence the quality of the rebounding echo. Curved surfaces and corners will give false readings, as shown in Figure 11. On a flat surface that is on a greater angle with respect to the transducer than the beam width, the oncoming sound wave will be reflected such that no echo is detected. The best environment for using ultrasound will consist of simple and consistently flat surfaces.

4.7.1.1/ Tests

Many tests were done with ultrasound on several surfaces. They are all included in Appendix A. Curved surfaces and altering the transducers angle to the reflecting target were both shown to cause erroneous readings.

The interior of a subway car was examined and experimented on with ultrasound. Certain areas with curved sections, which are located under the seats, gave false measurements. At the base level, however, the majority of the reflecting surfaces are simple flat grills or sheet metal, which reflect sound waves quite satisfactorily.

4.7.2/ Surface Composition

Different materials reflect and absorb different frequencies. Off-the-shelf ultrasonic units operate in the 50 to 60 kHz region. Some materials in an operating environment might not reflect sound at these frequencies. There is also the possibility of getting different readings from objects at the same distance but of different composition.

4.7.2.1/ Tests

Several materials were tested in the lab. Only foam rubber would not reflect ultrasound. Metal, glass, plastics, and wood showed little variation in their reflective characteristics. All materials that compose the interior of a subway car reflected sound waves adequately. Tests are summarized in Appendix A.

4.8/ Speed

If ultrasonic measurements are taken from a moving platform, such as a mobile robot, then a number of new error sources evolve, and greater care must be taken in interpreting readings. (This will be covered in the future report on using ultrasonics for bridge height measurement.)

4.8.1/ Sample Rate

Consider, once again, the sample rate at which measurements are performed. Suppose that readings are being executed from a moving platform and used for guidance purposes. Between successive samples, the robot is "blind," not knowing how far away objects are. One must consider how far the cart will move between samples to measure the uncertainty in position. This uncertainty in position is greater as the velocity of the cart increases and/or the sample rate decreases (Figure 12).

For example, assume that the robot cart is travelling at 1 m/s and vary the sample rate. If sampling is at five times per second, each cycle will take 200 ms. Before the next sample is taken, the platform will have moved 20 cm. By sampling at 30 times per second, each cycle decreases to 33 ms and the robot only moves 3.3 cm before the next reading is executed. Thus, at a fixed speed, as the sample rate is increased, the robot does not travel as far away from the position where the last measurement was taken. It is more sure of its position.

4.8.2/ Single Sample

One must also consider how far the moving vehicle will travel during the execution of a single sample. This will depend on the velocity of the cart and the distance to the target in question.

For example, estimate the speed of the robot again at 0.5 m/s and assume that the platform is 1.0 m away from a target wall. The time for the sound wave to travel to the wall and back will take about

$$2 \times 1.0 \text{ m} \times 1/340 \text{ ms} = 0.0059 \text{ s.}$$

During this time, the cart will move at least
0.5 m/s x 0.0059 s = 0.00295 m = 2.95 mm

For a particular sensor, this could be quite acceptable; however, if five or six sensors are to be read before the guidance MPU performs its calculations, then this factor compounds into a sizable delay (Figure 13).

4.9/ Interference

Ultrasonic systems operating in the 40 to 60 kHz region will be susceptible to interference from any other device generating these frequencies. The most serious sources of possible interference will be from other sonars operating in the region. With precautions, however, this problem can be minimized. Interfering sensors could be activated at different times, and horns can be used to reduce the beam width, thus shrinking the areas of interference.

4.9.1/ Tests

Both in the lab and in a subway car, operating a second sonar at the same time beside a test unit produced interference and erroneous results. Neither electromagnetic nor sound energy generated by microcomputers and motors appeared to effect the ultrasonic systems [5].

4.9.2/ Vibration

A major consideration is the vibration to which the transducer is subjected. When a fine resolution is desired, this factor becomes even more important. Consider the mobile cleaning robot. Motors, vacuums, generators, and the floor surface of the subway car will all be sources of vibration. These will have to be damped, and careful attention will be required in designing a transducer mounting. A mounting suggestion is included in Appendix B.

4.9.2.1/ Tests

The vibrations from an industrial vacuum cleaner were found to cause no interference when the sonar was placed directly on the vacuum's outer shell. See Appendix A for details.

5/ EQUIPMENT ON THE MARKET

Two ultrasonic packages were examined for use as part of the guidance system for the mobile robot project. They were the Polaroid ultrasonic ranging system and the Texas Instruments SN28827 sonar ranging module. Both made use of a single Polaroid instrument grade transducer as both transmitter and receiver. Data sheets for each device are included in Appendices C and D.

5.1/ Polaroid Ultrasonic Ranging System

This unit comes with a small circuit board and the Polaroid transducer (Figure 14). A timing diagram is included in Figure 15, as well as a diagram of the board with some necessary support circuitry. As illustrated, these additional circuits are required to operate the unit.

Upon application of power (VSW), there is a short variable delay and then the board initiates a series of pulses to the transducer. This consists of 56 pulses at four different frequencies, lasting about 1 ms in duration. After the transmitted energy has decayed to a sufficient level, the transducer begins to act as a receiver and listens for the echo. When this is detected, the FLG signal is raised.

The range of this device is from 27 cm to 10.7 m. Modifications can be made to reduce the minimum range to under 27 cm. As well, Polaroid supplies examples of the necessary support circuits needed to adapt the sonar to various uses.

For a detailed description of this unit's operation, please see the data and references included in Appendix C.

5.2/ Texas Instruments Sonar Ranging Module

This unit, shown in Figure 16, consists of a small circuit board and the Polaroid transducer. Figure 17 shows a timing diagram.

In contrast to the Polaroid unit, little support circuitry needs to be built to operate this range finder. Power (V_{CC}) is applied constantly to the board, and measurements are initiated with the INIT signal being raised. At this same instant, 16 pulses of 50 kHz are sent to the transducer and transmitted. To allow for the transmission energy to decay sufficiently, there is a delay of 2.38 ms before the transducer begins to act as a receiver. Upon recognizing an echo, the ECHO signal is brought to V_{CC}. INIT can then be brought low, bringing ECHO low as well, and a new measurement begins when INIT is again raised high.

The range of this unit is from 40.5 cm to 10.7 m. As well, the capability exists to easily reduce the minimum range below 40.5 cm. Full details are provided in Appendix D.

5.3/ Polaroid Transducer

Both ultrasonic units examined made use of the Polaroid instrument grade transducer. A thin foil is the moving part which transforms electrical energy into sound waves and sound waves into electrical energy. This foil is stretched over a metallic back plate forming a capacitor. When charged, an electrostatic force is exerted on the foil. Thus, when the small circuit board sends an ac signal at a given frequency, the foil moves at the same frequency to send out sound waves.

5.4/ Comparison

The Polaroid device is the same circuit board used in the company's auto-focusing cameras. Thus, as was shown, some external circuitry is required to adapt it to other uses. Also, it has a rather long duration of transmission involving four different frequencies. For simple reflecting surfaces, only one frequency, transmitted for a few micro-seconds, is needed. One aspect of its operation that could cause problems in a guidance systems design is that there is a random delay between initiating a measurement and the actual transmission of pulses.

The Texas Instruments module was designed to be more adaptable to other uses. It will transmit the pulses as soon as the signal to initiate a measurement is given. It transmits only one frequency for 320 μs and requires very little support circuitry to run and interface to a computer.

6/ REQUIREMENTS OF THE GUIDANCE SYSTEM

For the mobile robot project, a guidance system incorporating ultrasonic range finders is required. To design this system, a detailed mandate is needed as a guideline. This is accomplished in three parts. First, in Section 6.1, a general description of what is needed is given. Then, selected key issues and desires are noted and justified in Section 6.2. Finally, Section 6.3 summarizes design requirements.

6.1/ General Description

The guidance system should be capable of measuring the distance from the robot to objects surrounding it in a subway car environment. The system should be capable of performing calculations on the measurements and be able to communicate information to a host computer.

6.2/ Specific Requirements

Listed are a series of requirements for the guidance system and its incorporated ultrasonic modules.

6.2.1/ Number of Sonars

Six sonars are positioned on the mobile robot: two on each side and one each on the front and back. The front and rear modules would be used during entry and exit to and from the transit vehicle and when it approached an end wall. The four side sensors are to be used in keeping the cleaning cart parallel to the walls as it progresses down the length of the subway car.

6.2.2/ Range

The maximum range of the four side sensors should be about 1.5 m. This is the most that the robot should be from any side wall after it has initially entered the subway car. The two remaining sensors should have a maximum range of 3.1 m. This should enable detection of the opposite doors during the entry phase and offer early front and rear detection of the centre stanchions.

It is desirable to have the minimum range as small as possible. The cart is expected to come within approximately 5 mm of some surfaces.

The range of each sonar should be easily alterable or programmable. Updates and changes can be expected once a detailed trajectory is calculated and if the ultrasonics are to be used outside of the transit

vehicle. If a sensor does not detect an object in its range, the guidance system should be capable of recognizing this fact.

6.2.3/ Resolution

A 1 mm resolution is required for the guidance system. This is necessary to quickly determine if the robot is swaying away from its programmed route. As well, it will be essential during extension of the cleaning arm. Note that repeatability is very important and may require averaging several readings.

6.2.4/ Temperature and Humidity

The following range in temperature is expected assuming the robot will be used outside.

During Use	During Storage
-25 C to 40 C	-35 C to 70 C

The following range in humidity is expected.

During Use	During Storage
95% non-condensing	95% non-condensing

Some form of water cleaning is expected to be done by the robot.

6.2.5/ Reflecting Surfaces

The guidance system must operate inside a subway car and be capable of taking measurements at the base level (0 to 27.5 cm above the floor) from the existing reflecting surfaces.

6.2.5.1/ Surface Composition

The guidance system should be capable of operating off the following surfaces.

Metal
Glass
Plastics

6.2.5.2/ Surface Geometry

The majority of the surfaces at the base level of the subway car are flat metallic grills. The remaining surfaces are complex consisting of curves under the seats, metal poles, and entrance walls.

6.2.6/ Ultrasonic Modules

It has been decided to use the Texas Instruments ultrasonic ranging modules as the sonars on the guidance system. This choice was made because of their simplicity and ease of interfacing to a computer system.

The transducers should be the Polaroid instrument grade models or the newly introduced environmental grade, and a beam width of under 10° is desired. Acoustical horns will, thus, be needed.

6.2.7/ Processing

It is expected that the guidance system will be required to process at least some of the measurements and, possibly, even calculate deviations from the trajectory.

As of now, the host computer, to which the guidance system will communicate, is not yet known. It is anticipated that this host will be able to communicate with a peripheral interface adapter (PIA). In the prototype guidance system, one PIA and one asynchronous communications interface adapter (ACIA) port should be allowed to transfer data to the host.

It should be possible to selectively use or shut off each of the six sensors. This is necessary since there are some regions in the subway car where individual sonars can interfere with the others. As well, the front and rear sonars will most likely only be used at the ends of the rail car and during entry and exit phases.

It should be possible to activate the sonars individually at different times and in different sequences from each other. This is because all modules will take a different time to perform a measurement, depending on the distance being recorded. When one sonar reads a large range, it is possible to take multiple measurements of shorter distances during the same time with the other sensors.

A signal labeled ECHO is available on the sonar module and indicates when that unit has detected an echo. When an echo is detected, it should be possible to generate an interrupt to the microprocessor. There should be an individual interrupt signal from each module. This is to make the

software design more flexible.

As each sonar reading is performed, data should be immediately processed and made available to the host. The host should not have to wait for the slowest measurement of the selected sensors to be completed before it can process data.

6.2.8/ Robot Speed

Anticipate the speed of the robot to be no more than 0.3 m/s. It is expected that it will have to slow down on many occasions to execute complex arm movements.

6.2.9/ Noise and Vibration

The guidance system must be immune from all noise interference sources likely present on a subway car and from devices on the robot. Some type of small engine will be placed on the robot to power the vacuum cleaner, generate electricity, etc. This will likely be a major source of vibration, so transducer mountings should offer sufficient damping to eliminate this interference.

6.3/ Summary of Requirements

Number of Sonars:	6
Type:	Texas Instruments SN28827
Resolution:	To 1 mm
Range:	5 mm to 3.1 m
Processor:	Motorola MPU preferable

Additional Comments:

- Must have the ability to activate/deactivate individual sonars.
- Must have the ability to activate/deactivate individual sonars at different selected times.
- Must have the ability to generate an interrupt when the echo returns.
- Must have the ability to process the data immediately after each echo returns.
- Must be able to function in an industrial environment.

7/ DESIGN CONCEPT

Examining the requirements, a prototype design can be produced (Figure 18). The diagram shows a guidance computer interfaced to six ultrasonic modules, a counting circuit, and a host system. Three PIAs are required to communicate with the six modules and counting circuitry. Two PIAs could have been used; however, three offers room for expansion, thus greater flexibility.

Motorola micro-modules are suggested for the guidance MPU and PIA.

8/ TESTS

A series of tests was performed on the Texas Instruments sonar ranging module both in the lab and in an H5 subway car.

8.1/ Lab Test Summary

The lab tests were carried out to prove that the range finder performed to its specifications. All procedures and results are documented in Appendix A. It was shown that the unit gave repeatable and fairly accurate measurements and that the beam width could be successfully narrowed using acoustical horns. Over all, the tests indicated that the module performed to specifications and that it can be reliably used as a non-contact distance measuring device.

8.2/ Lab Test Conclusions

The Texas Instruments sonar and the support circuitry shown in Figure A14 were concluded to be quite capable of making a series of repeatable measurements if the test conditions remain fixed.

The accuracy of these measurements, however, has been found to vary by up to 6.5%. Some hypotheses for this include the following:

- counters clock rate not exactly at the desired 200 kHz;
- internal error in the Hewlett Packard (HP) counter used, or on the settings;
- transducer mounting not perfectly secure;
- target position or module and transducer placement not exact;
- temperature variations between tests and incorrect temperature value used during calculations (the speed of sound is very sensitive to changes in temperature);
- transducers membrane a few millimetres inset from the exterior of the transducer;
- interference from other objects, notably, the floor.

Also concluded was that the angle of the transducer to its reflected surface must be less than 10° if it is to perform accurately.

All materials tested except foam rubber will reflect ultrasound.

An object such as a pole is accurately detected until it gets to the outside boundary of the beam. In this region, readings become false and inconsistent as the object moves out of the beam's range.

The beam width of the Polaroid transducer is, as specified, 20°.

Acoustical horns work to decrease the beam width. A 134 mm long horn successfully reduced the beam width by half, to 10°.

Other ultrasonic units, simultaneously performing measurements beside the module, cause serious interference if aimed at the same targets.

Operating a vacuum nearby does not effect the the sonar module.

Vibrations from a vacuum, directly transferred to an operating sonar produced no adverse effect.

Overall, once the noise problem had been cured, the unit performed very well, giving good repeatable measurements. By using an appropriate calibration technique, a consistently high degree of accuracy may be achieved.

8.3/ H5 Subway Car Test Summary

A selection of tests was performed in an H5 subway car with the Texas Instruments sonar to verify that the unit was capable of measuring in that environment. Vibrating doors were found to cause a variation in measured readings, and curved sections under the seats produced erroneous results. Overall, however, the unit worked well in the subway car.

8.4/ H5 Subway Car Test Conclusions

It can be concluded that using sonars for distance measurements inside subway cars is feasible if the few areas producing inconsistencies are compensated for in the design.

The doors of the subway car were found to be vibrating when the train was stationary. Readings become subject to inconsistencies and will vary by a few millimetres between each sample. The actual distance can be obtained using averaging, and hence, the results are usable.

A small curved area under the seats cannot be sensed by the sonar. This represents a very small fraction of the total area, however, and can easily be circumvented.

Equipment under the train, such as compressors, will intermittently come on and off, but this appears not to cause any excess vibrations or measurement errors.

The sonar was positioned in all sections of the subway car and correctly functioned with no interference (excluding doors and curves under seats).

9/ CONCLUSIONS AND RECOMMENDATIONS

This report examines the feasibility of applying ultrasonic sensors to a guidance system in a mobile robot. It can now be concluded that a design, such as that of Figure 18, is feasible and that very few sections of a subway car will interfere with ultrasonic devices.

Two off-the-shelf ultrasonic modules were analyzed, and it was concluded that the Texas Instruments model would better suit the needs of this project. This unit was then extensively tested both in the lab and in the transit vehicles environment and found to operate quite successfully. It is thus recommended that it be used in the design of a guidance system.

Next, it was shown that the guidance system should be designed similar to that of Figure 18. It is concluded that this approach will offer the greatest flexibility and simplicity.

10/ REFERENCES

[1] Biber, C., Ellin, S., Shenck, E., and Stempeck, J., "The Polaroid Ultrasonic Ranging System," Polaroid Corporation, October 1980.

[2] Everatt, H.R., "A Multi-element Ultrasonic Ranging Array," Robotics Age, July 1985, p. 13.

[3] "Polaroid Ultrasonics Ranging System User's Manual," Polaroid Corporation, p. 14.

[4] Wang, J., Wambold, J.C., and Henry, J.J., "A Microprocessor Based Non-Contact Distance Measuring System," Transportation Research Record 1000, Pennsylvania Transportation Institute.

[5] "Polaroid Ultrasonic Sensors in Robotics Applications," Robotics Age, March 1985, p. 23.

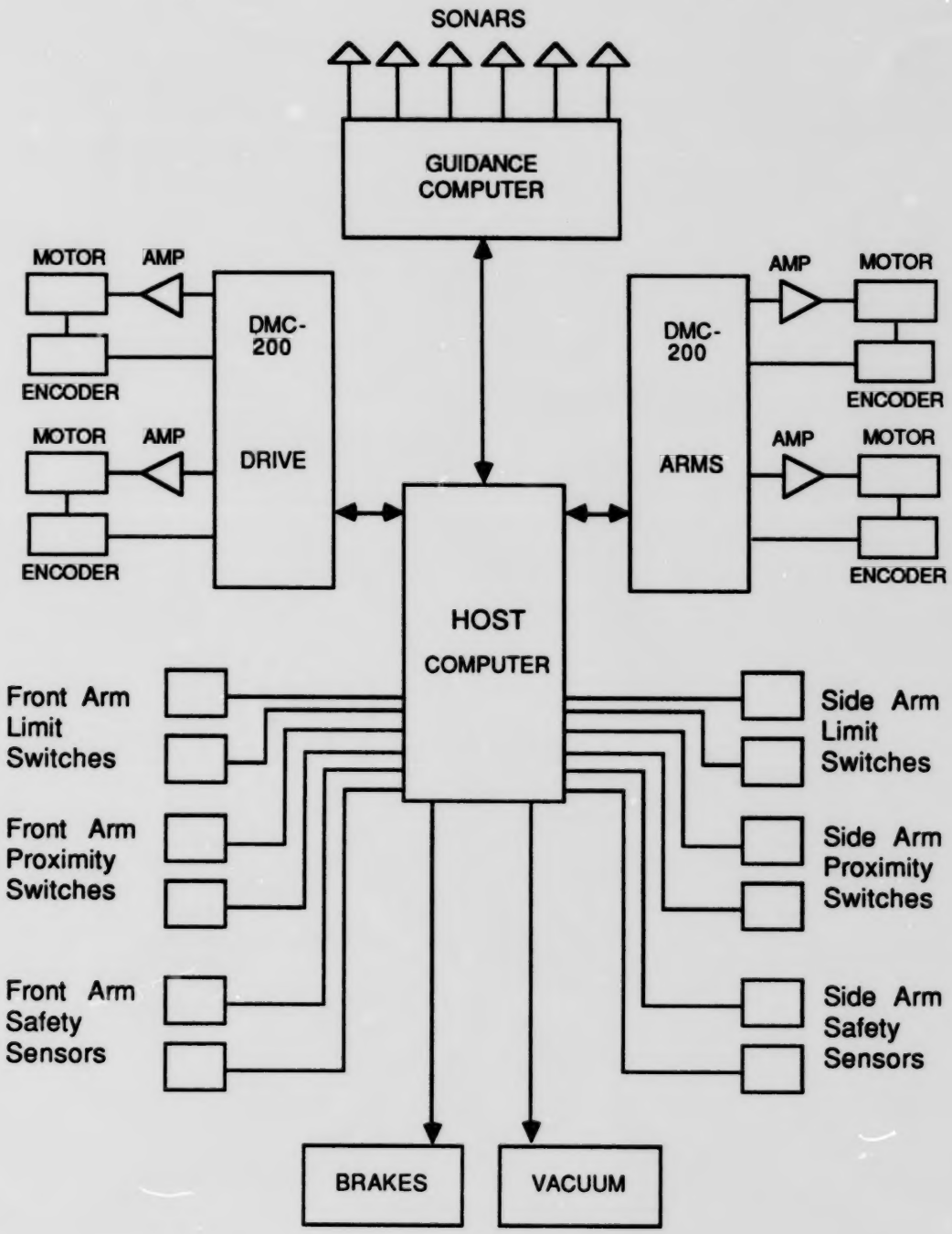


Figure 1/ General Block Diagram

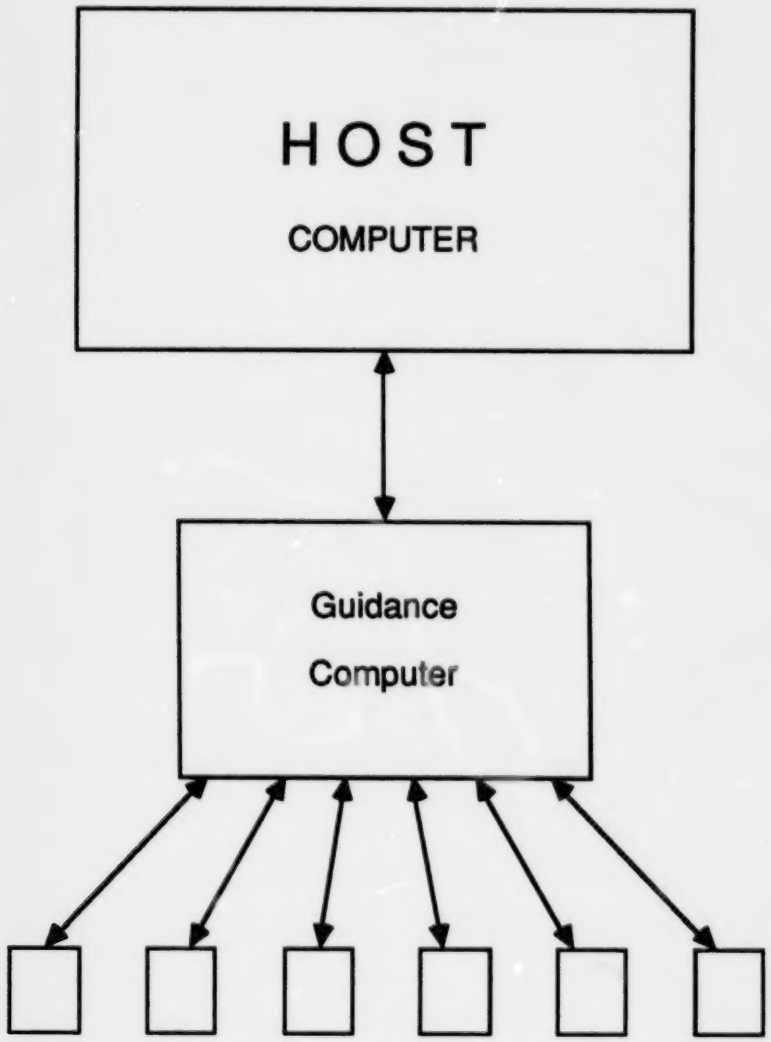
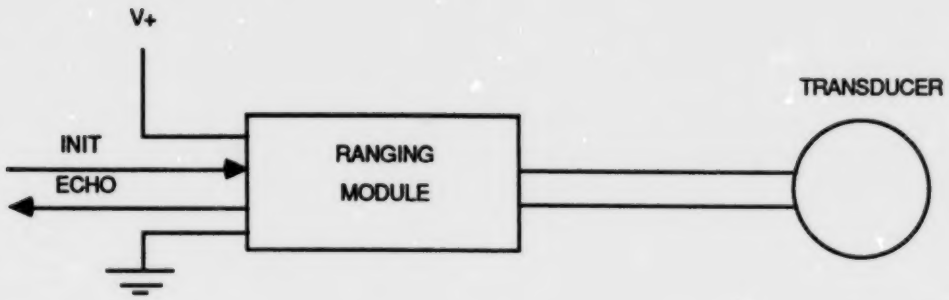


Figure 2/ Guidance System - Block Diagram



Timing Diagram

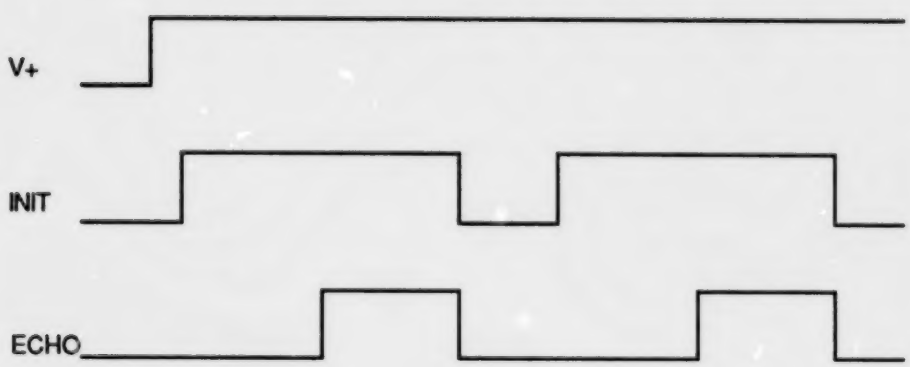
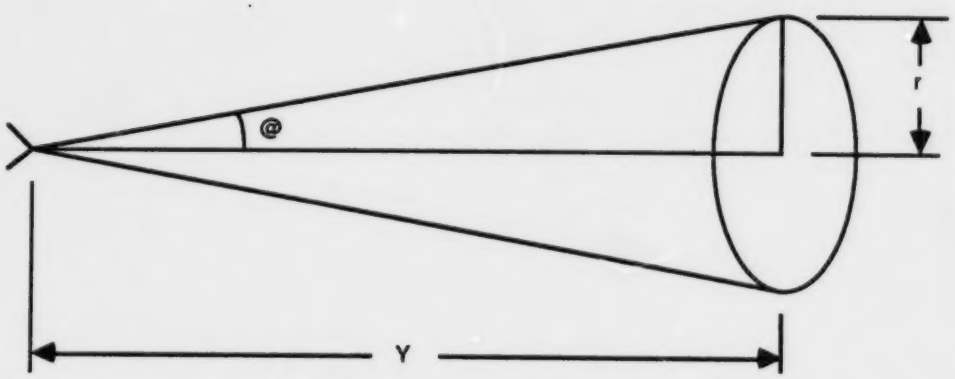


Figure 3/ A Typical Ultrasonic Module

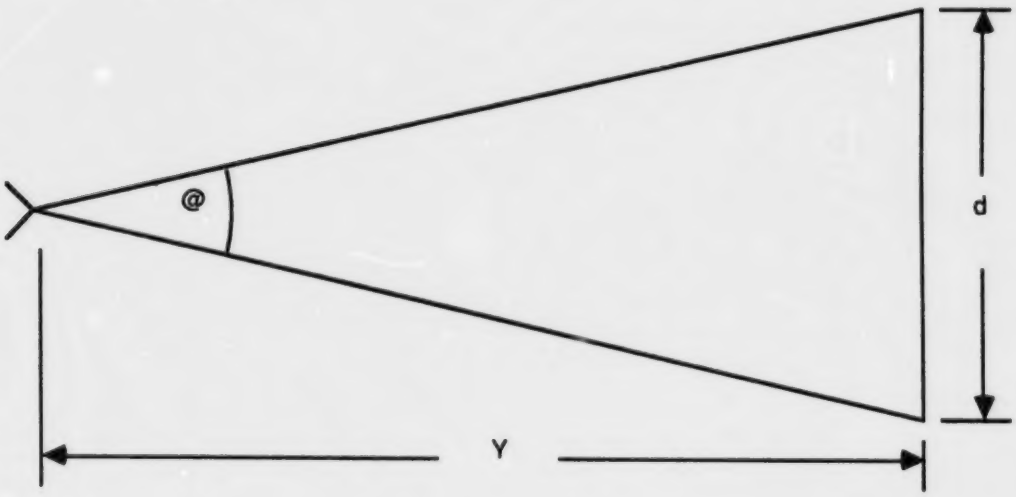
r = Y x TAN(@)



Different Ways to Alter Beam Width	
To Increase Beam Width	To Decrease Beam Width
- Add Acoustical Lens	- Add Acoustical Horn
- Decrease Frequency	- Increase Frequency
- Increase Transducer Diameter	- Decrease Transducer Diameter

Figure 4/ Beam Width

As the sensor is moved further away from the target, the diameter d of the coverage area increases. The radial beam width @ is fixed.



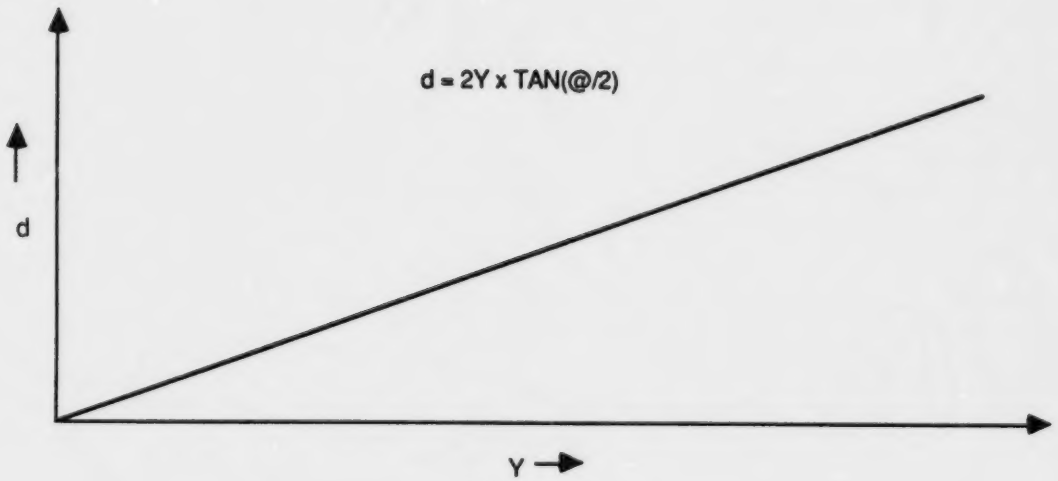
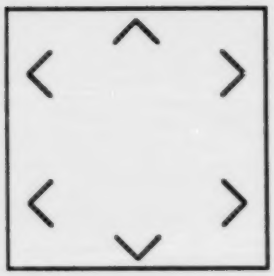
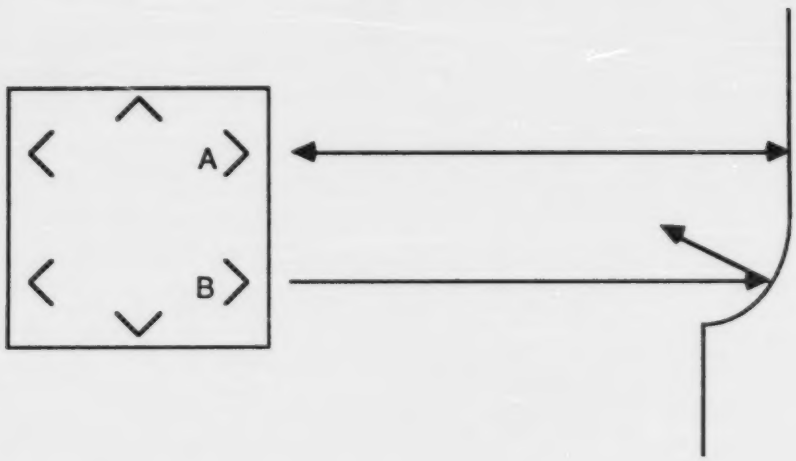


Figure 5/ Coverage Area vs Distance

Full Coverage - All Sides



Wide Spacing



Sensor B reads a false distance due to its signal reflecting off of a complex surface and could also interfere with sensor A. Proper spacing and triggering of sonars will ensure that at least one side sensor gives correct data.

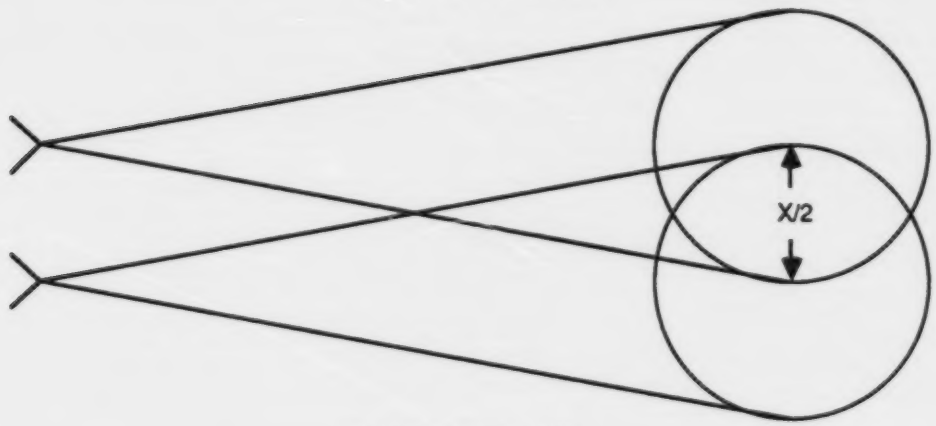
Figure 6/ Placement Patterns

Using One Sensor

Coverage Area = X
Uncertainty = X

The object detected could be anywhere within the area of diameter X.

Using Two Sensors

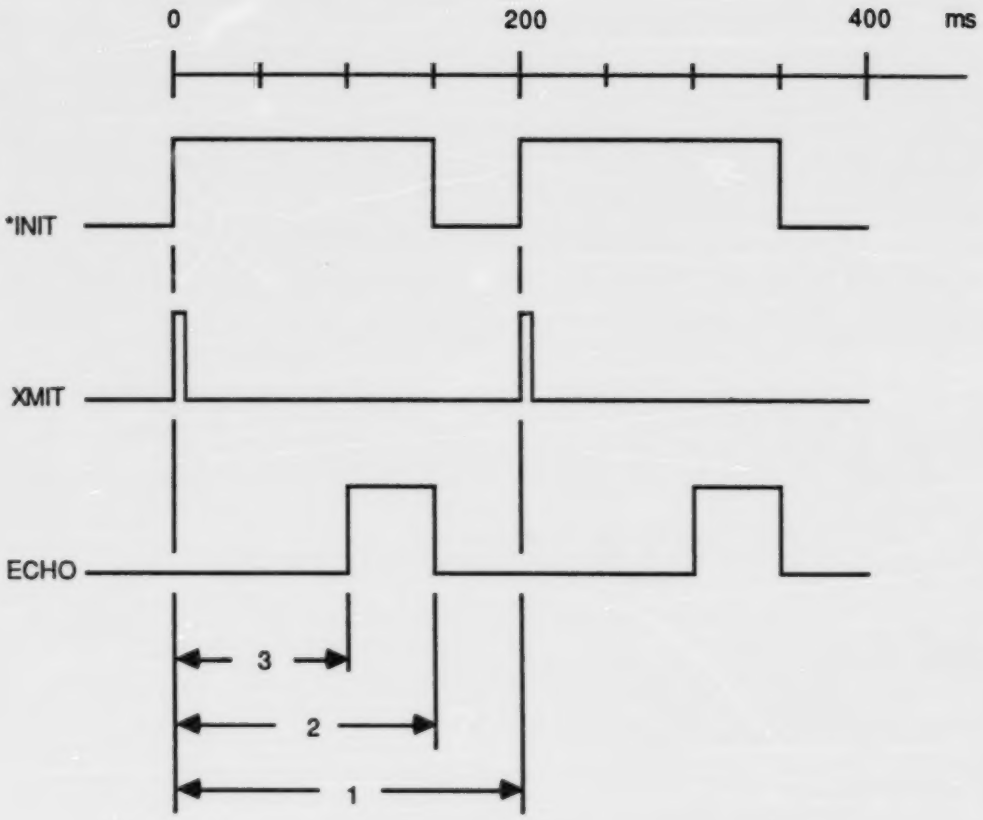


Coverage Area = 3X/2
Uncertainty = X/2

By using beam splitting, objects can be located with a lower area of uncertainty.

Figure 7/ Beam Splitting

i) A sample rate of 5 times/s



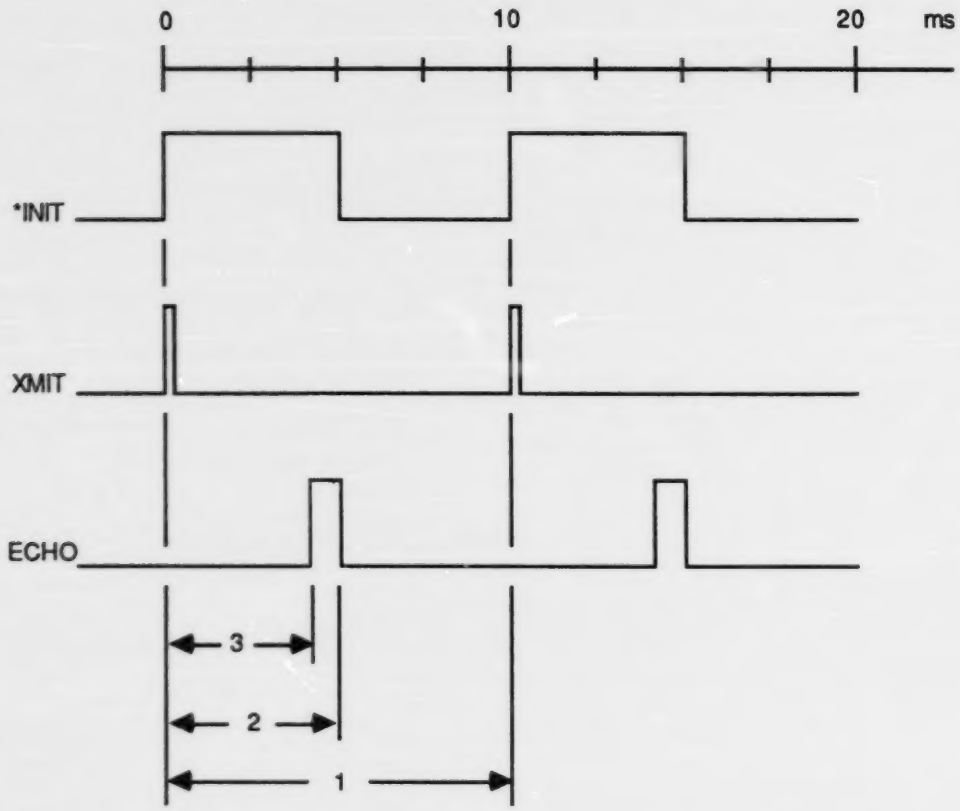
1 Cycle period = 200 ms
2 Maximum allowable echo time = 150 ms
3 An echo time of 100 ms

The maximum allowable echo time is determined by the time of each cycle during which INIT is high. For 150 ms, this imposes a maximum range of 25 m.

*INIT is the control signal that starts the timing sequence.

Figure 8/ Sample Rate vs Range

ii) A sample rate of 100 times/s

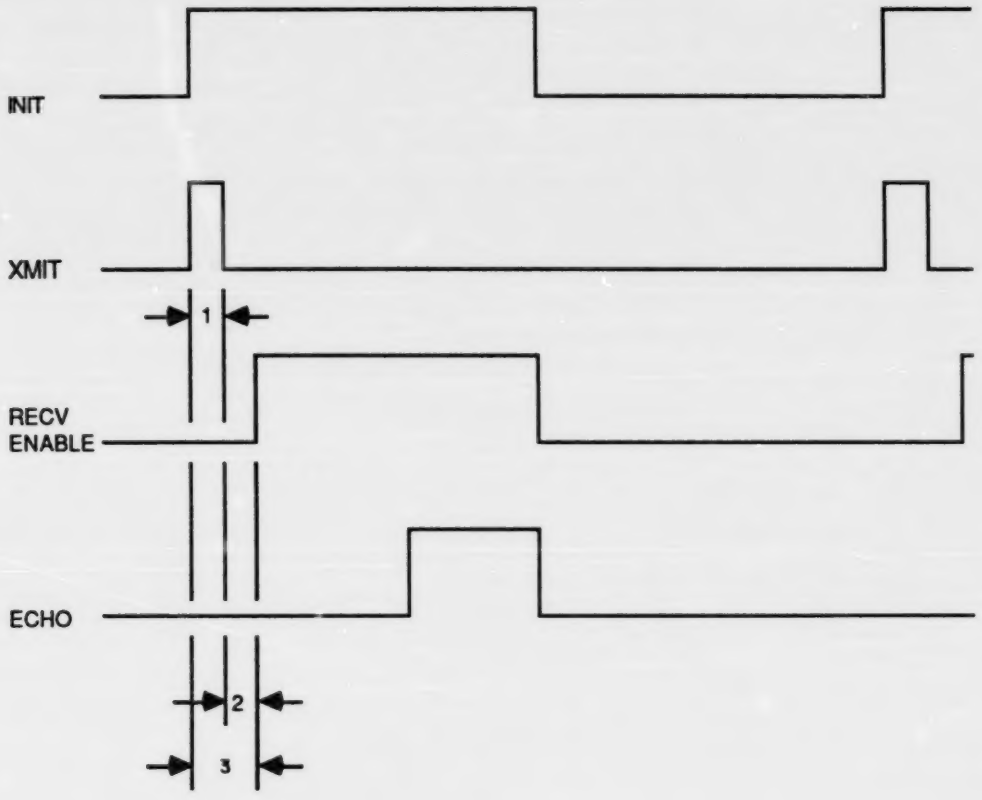


1 Cycle period = 10 ms
2 Maximum allowable echo time = 5 ms
3 An echo time of 4 ms

The maximum allowable echo time is determined by the time of each cycle during which INIT is high. For 5 ms, this imposes a maximum range of 0.85 m.

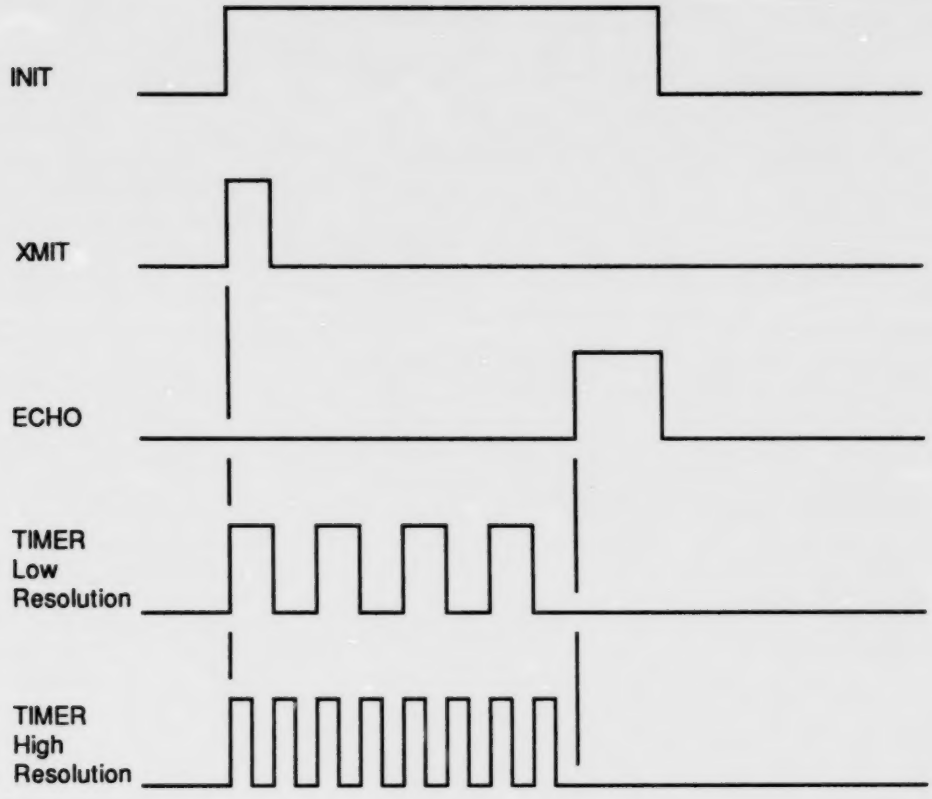
*INIT is the control signal that starts the timing sequence.

Figure 8/ Sample Rate vs Range (cont'd)



1. Transmit time
2. Time allowed for transducer energy to decay
3. Total delay time (determines minimum range)

Figure 9/ Transmission Time/Energy Decay Time vs Minimum Range



$$\text{Distance to Target} = \frac{\text{Speed of Sound (m/s)} \times \text{Timer Count (s)}}{2}$$

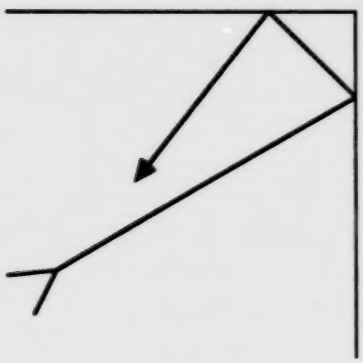
Figure 10/ Resolution

Case A

- Smooth surface
- No echo received due to scattered beam.

Case B

- Corner
- Sensor indicates larger distance than actual due to reflected beam.



Case C

- Curved surface
- No echo received due to scattered beam.

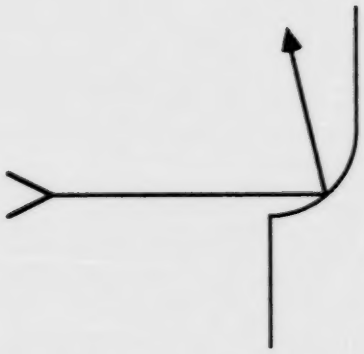
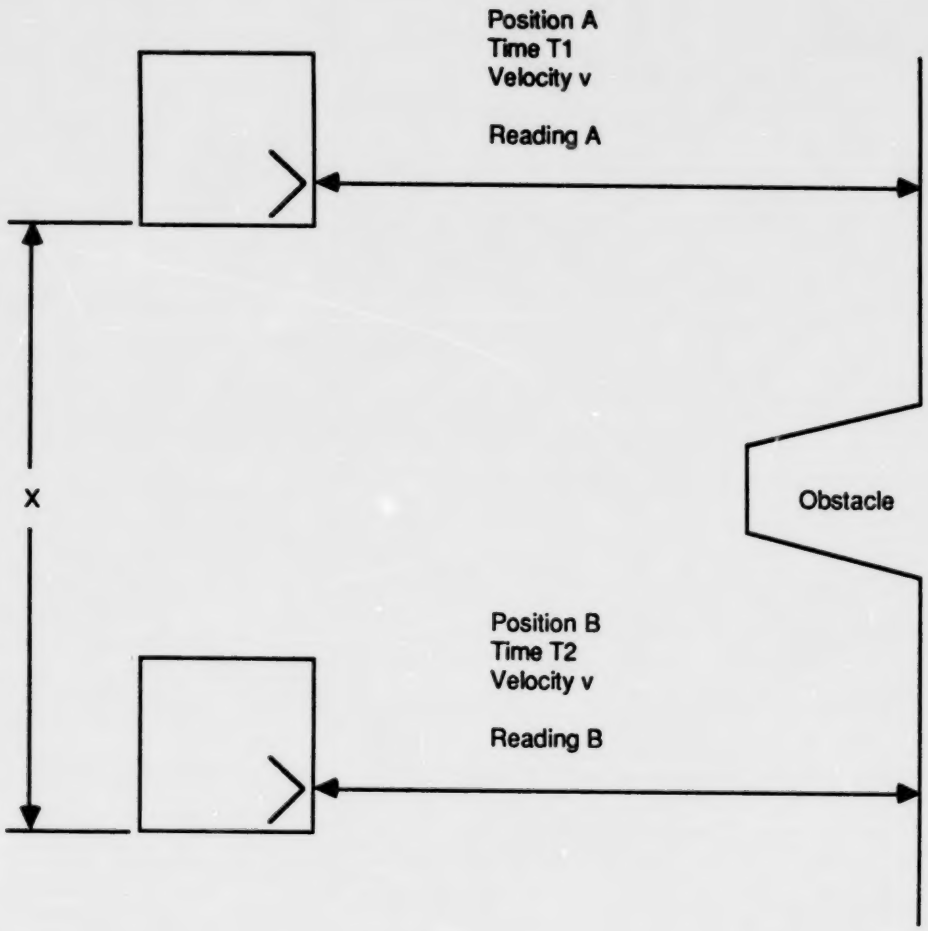


Figure 11/ Distortion by Complex Surfaces



At time T1, the robot is in position A and travelling with a velocity v. The first measurement, reading A, is taken.

At time T2, the robot is now in position B, still travelling with a velocity v. Here a second measurement, reading B, is taken.

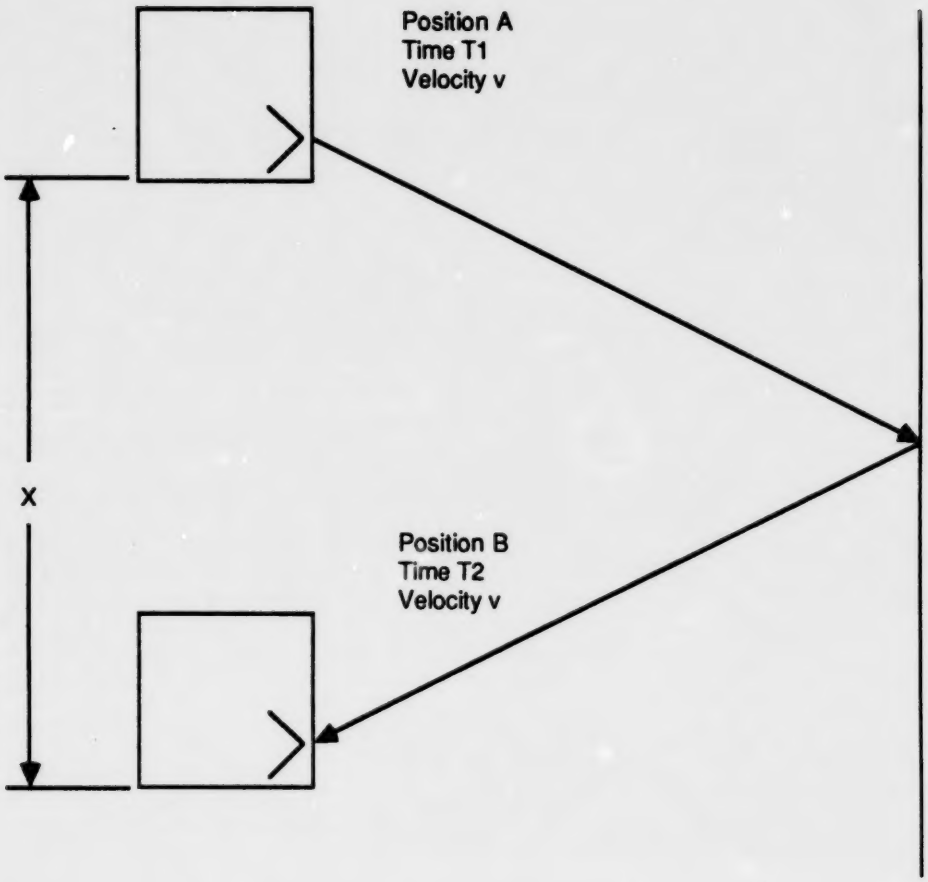
If the time between readings is too long, the distance X that the robot travels may be so large that objects may be missed and cause the robot to stray off course.

Example:

velocity v = 1 m/s

If the sample rate = 5 times/s then the distance travelled X = 0.2 m.
If the sample rate = 30 times/s then the distance travelled X = 0.033 m.

Figure 12/ Velocity vs Sample Time



Example:

Velocity v = 0.5 m/s

If the cart is located 1.0 m from the wall, the time to transmit and receive the echo is 0.0059 s. In this time the robot will have travelled a distance X of 0.00295 m or 2.95 mm.

Figure 13/ Sample Length

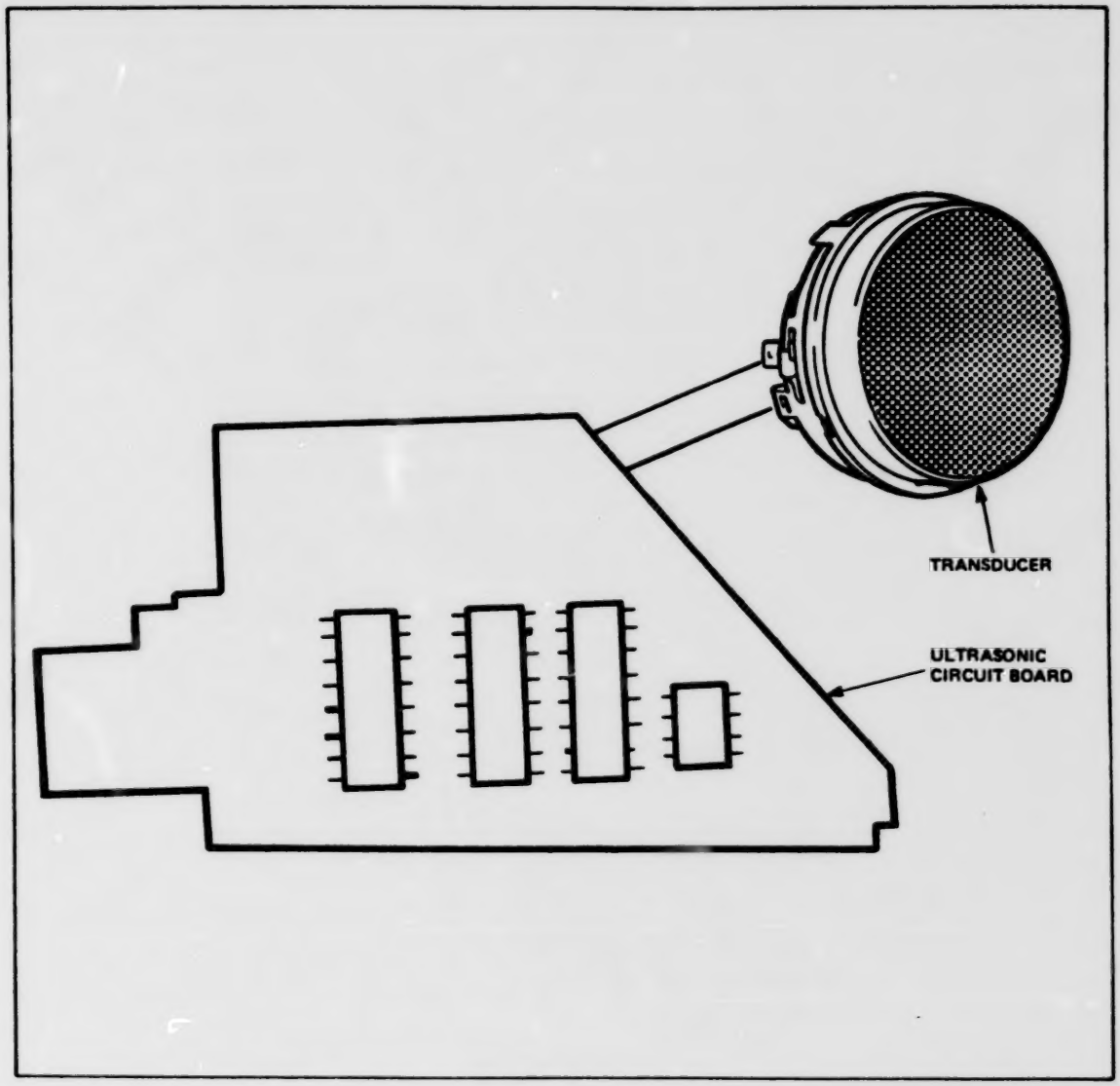
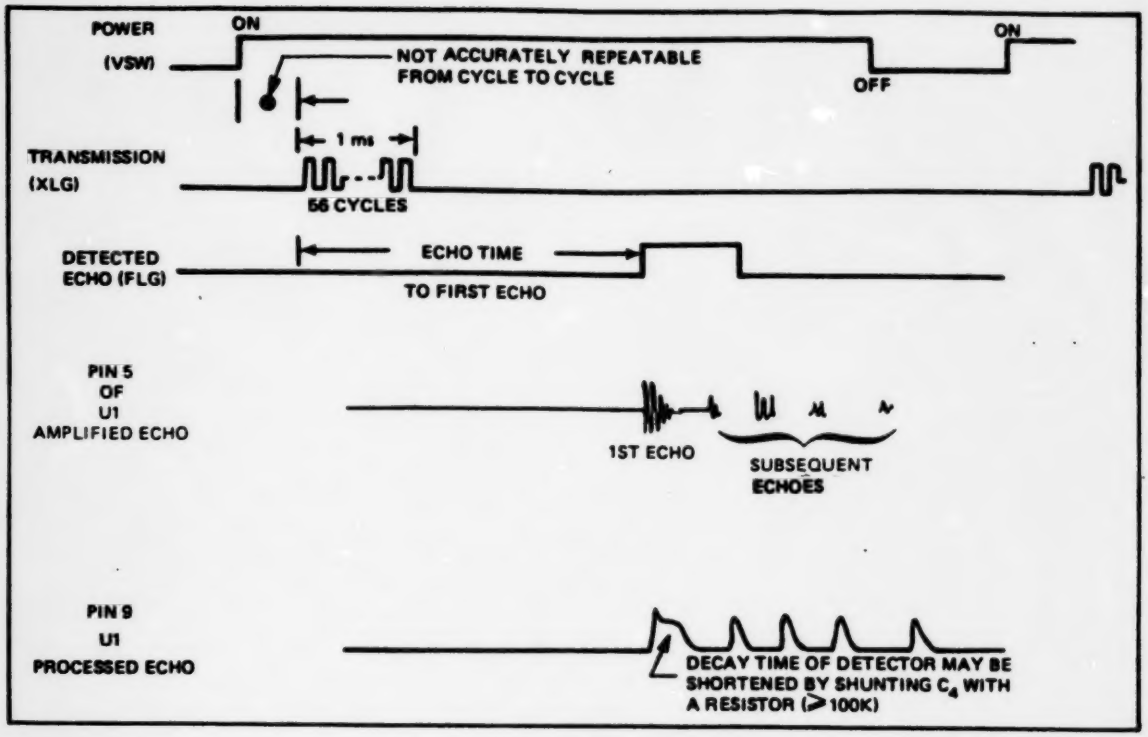


Figure 14/ Polaroid Ultrasonic Ranging System



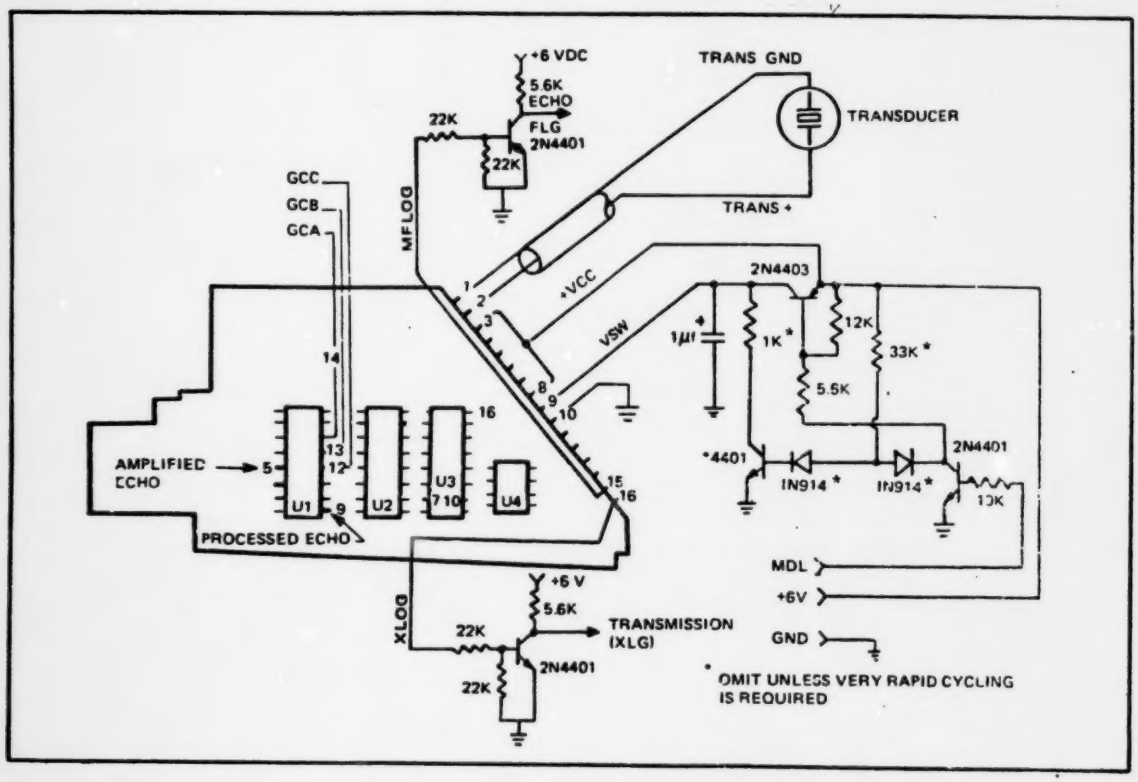
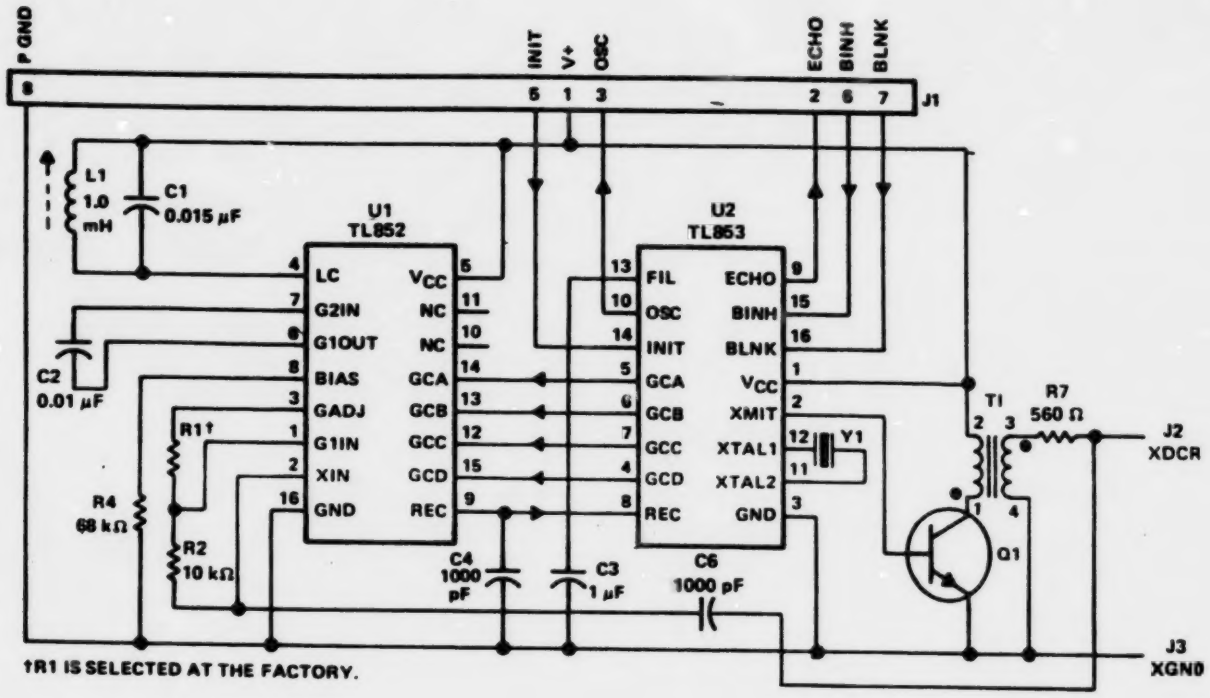


Figure 15/ Polaroid Timing Diagram and Circuitry



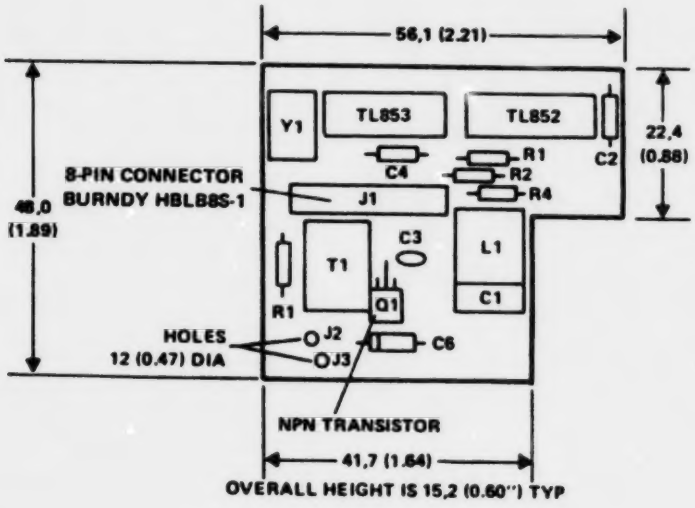


Figure 16/ Texas Instruments Sonar System

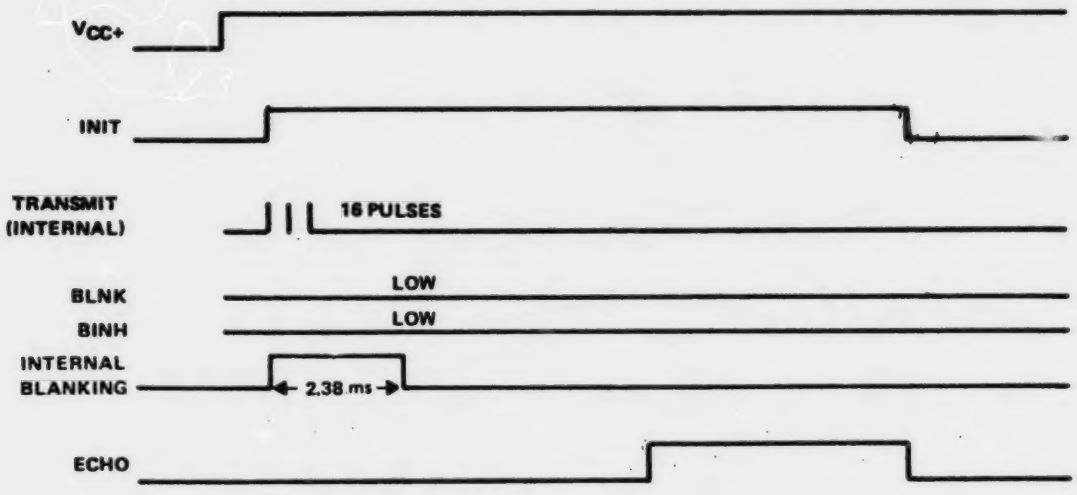


Figure 17/ Timing Diagram - Texas Instruments

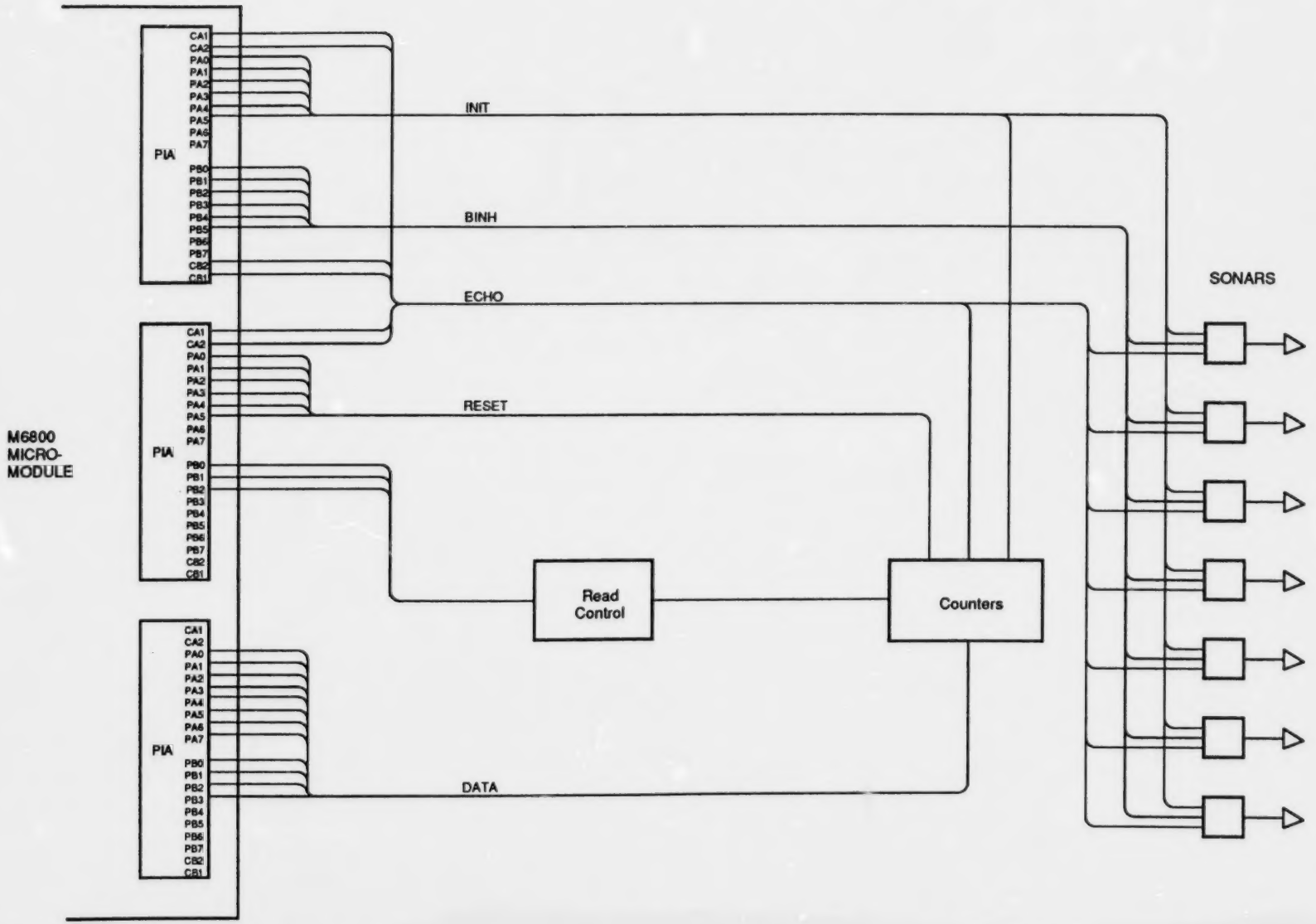


Figure 18/ Guidance System Design Concept

APPENDIX A/ TEST SECTION

APPENDIX A/ TEST SECTION

This appendix contains two major parts:
1/ Part I: Lab Test
2/ Part II: Subway Car Test

PURPOSE

These tests examine the characteristics and operation of the Texas Instruments sonar ranging module using a Polaroid instrument grade transducer. They were conducted to verify that the sonar unit could be used as an accurate non-contact distance measuring device in the design of a guidance system for a mobile cleaning robot. The robot is being designed for use in an H5 subway car.

Part I was carried out in the lab, and Part II was done in an H5 subway car.

Please note that variation in the speed of sound due to temperature fluctuations is not compensated for in every reading. Room temperature was measured once before testing and was found to be 23°C. At this temperature, the speed of sound is 345 m/s and has been used in all calculations. Many measurements, while highly repeatable, are found to be off by as much as 9 cm, and it is suspected that the cause of error is the taking of 345 m/s as the constant value for the speed of sound, without accounting for temperature change in different experiments.

Also note that in some tests the distance from the sonar unit to the object is not given as only relative changes in distance measurements are of any importance.

Part 1/ Lab Test

CHARACTERISTICS TESTED

The following characteristics of the TI sonar ranging module and the Polaroid instrument grade transducer were examined.

Accuracy
1.1/ Resolution Verification
1.2/ Distance Verification
1.3/ Clock Rate
1.4/ Repeatability

The Effect of Different Positions
2.1/ Height
2.2/ Angle to Reflected Surface

The Effect of Different Surfaces
3.1/ Different Materials
3.2/ Different Objects - Poles
3.3/ Different Objects - Dividers

Beam Width
4.1/ Measure Beam Width
4.2/ Acoustical Horns

Interference
5.1/ Between Two Units
5.2/ From a Vacuum at Close Range
5.3/ From Vibration

OPERATION

Figure A1 illustrates the experimental setup. It consists of the TI sonar unit and its Polaroid transducer, a 1 Hz signal generator, a 200 kHz signal generator, a counter, and small circuit board of logic gates. To initiate a measurement, INIT must be brought to +5 V. This is accomplished either manually (switch) or at repeated intervals of 1 Hz from a slow clock (auto). As soon as INIT goes high, a high-frequency clock (200 kHz) from a signal generator is patched through to a counter and it begins counting the clock pulses. At the same time, the TI board transmits 16 pulses at 50 kHz through the connected Polaroid transducer. Then the transducer is used as a receiver, and the TI board listens for an echo. When an echo is detected, the TI board raises the ECHO line to +5 V and the logic circuit disconnects the high-frequency clock from the counter. A display on the counter shows the elapsed number of cycles.

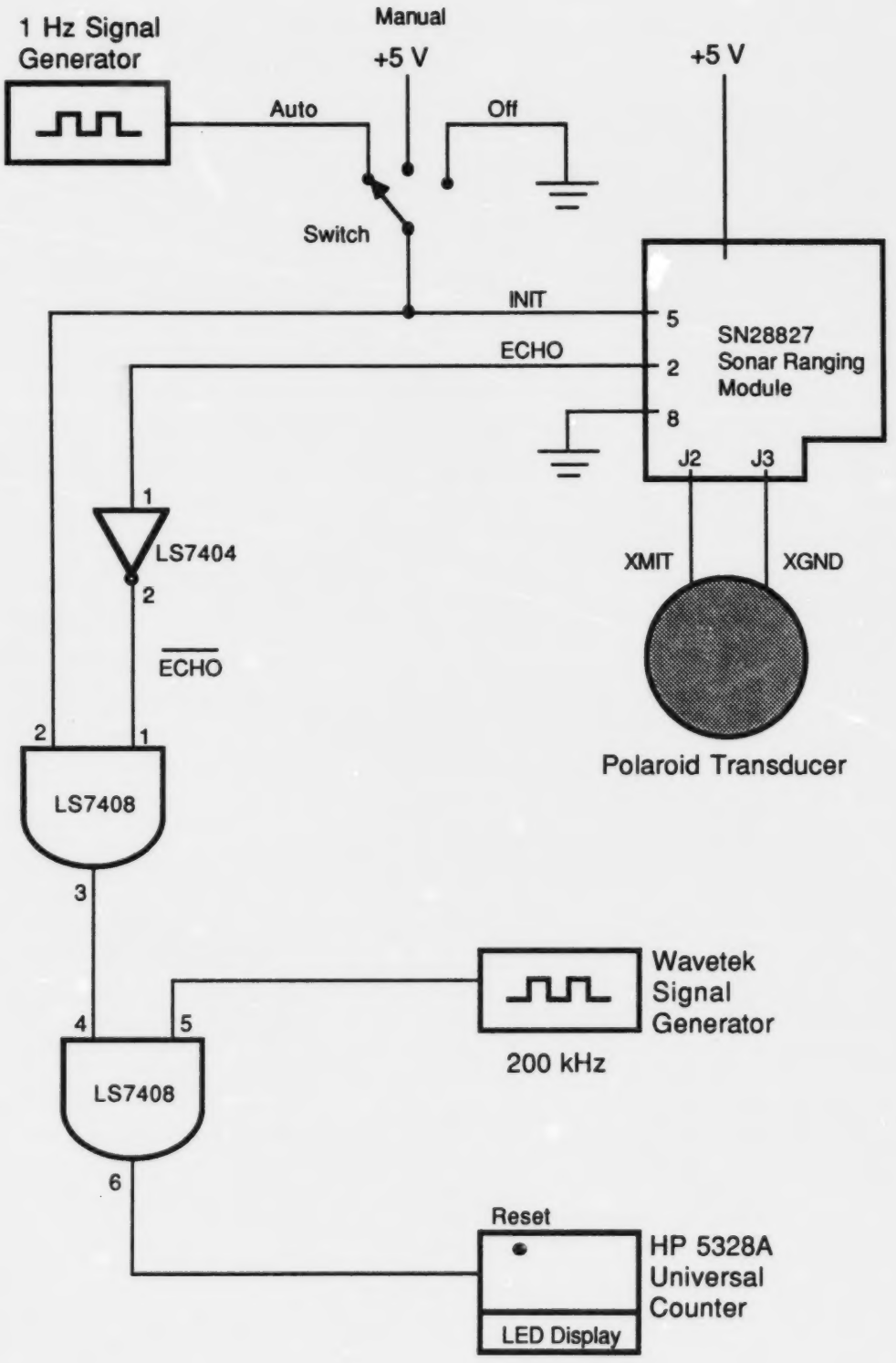


Figure A1/ Experimental Setup (March 11)

DISTANCE CALCULATION

Knowing the frequency and the elapsed count, a distance to the target is simply calculated by

$$\text{Distance (mm)} = \frac{\text{Speed of Sound (m/s)} \times \text{Count} \times 1000}{\text{Frequency (Hz)} \times 2}$$

$$= \frac{345 \text{ m/s} \times \text{Count} \times 1000 \text{ mm/m}}{200\,000 \text{ Hz} \times 2}$$

$$\text{Average Error \%} = \frac{\text{Actual Distance (mm)} - \text{Calculated Average Distance (mm)}}{\text{Actual Distance (mm)}} \times 100\%$$

TEST RESULTS

The test period lasted from March 11 to March 26. It can best be divided into three sections:

1/ The first section consists of tests run in the first week. These show that the device performs to the specifications set by Texas Instruments but also indicate that the results are not accurately repeatable from one measurement to the next.

2/ The second section illustrates why this problem was occurring and how it was corrected.

3/ Finally, with the new correction, the initial tests were repeated. The third section shows these results.

SECTION 1
March 11 to March 17

TEST: 1.1 Resolution Verification.

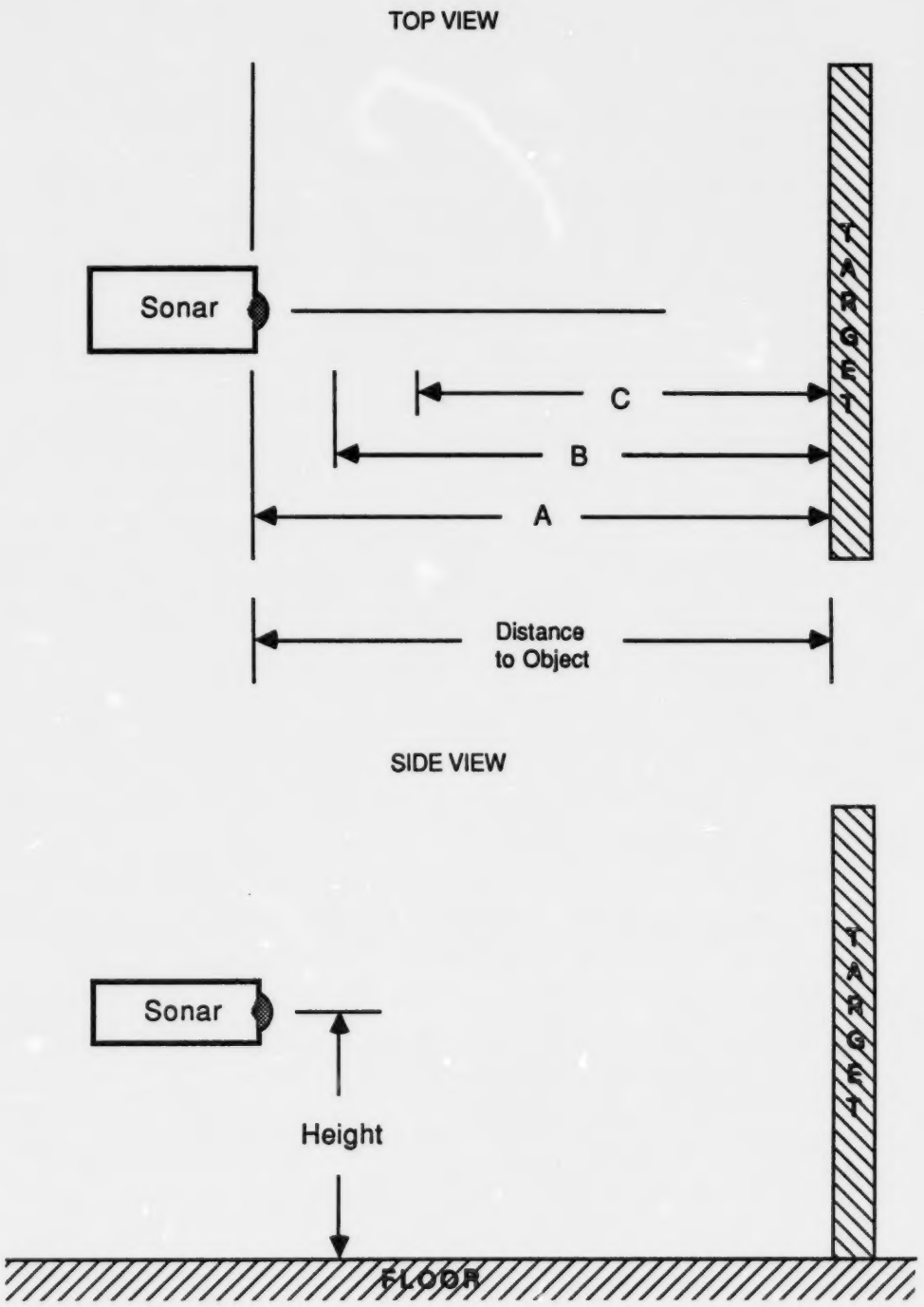
DATE: March 11/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a flat plywood wall at a distance A. 10 readings were taken. Then the sonar was moved closer by 5 mm to position B. 10 more samples were taken. This was again repeated. The aim of this test was to see if the sonar could detect a change of exactly 5 mm in distance.

MEASUREMENTS: A = 2591 mm to Target Wall
B = 2586 mm " " "
C = 2581 mm " " "

	A	B	C	
	Count	Count	Count	
1	2955	2948	2944	
2	2957	2949	2946	
3	2955	2949	2946	
4	2951	2949	2944	
5	2955	2948	2944	
6	2958	2950	2958	
7	2955	2951	2945	
8	2955	2948	2944	
9	2955	2948	2944	
10	2956	2950	2944	
Average Count	2955	2949	2946	
Average mm	2549	2544	2541	
%	1.6	1.6	1.6	



Test 1.1/ Resolution Verification

TEST: 1.4 Repeatability

DATE: March 17/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

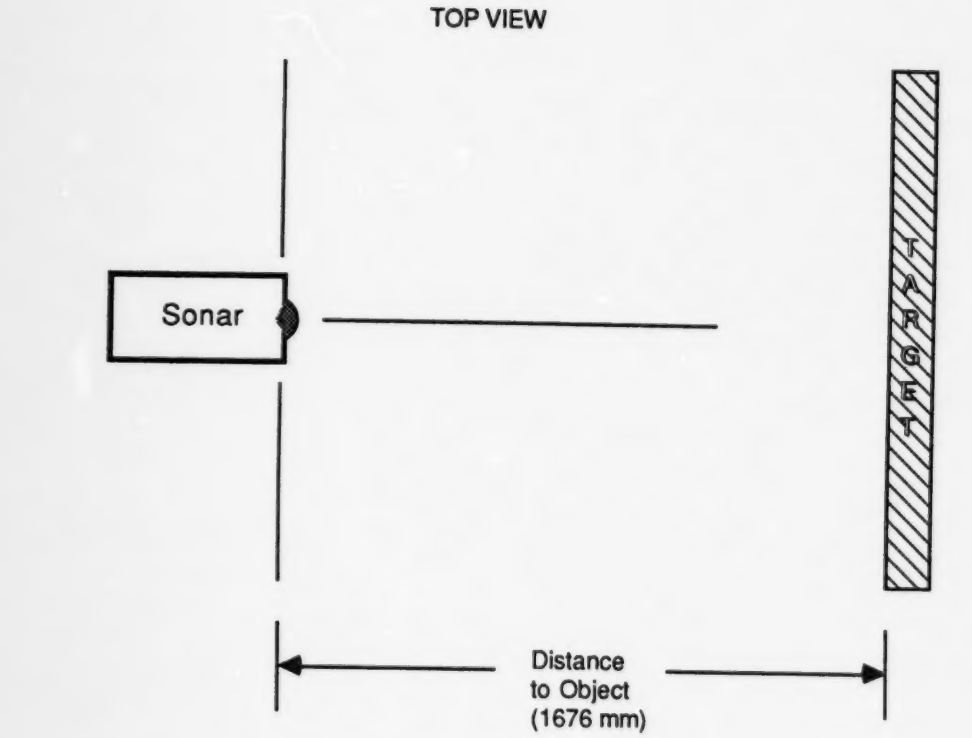
DESCRIPTION:

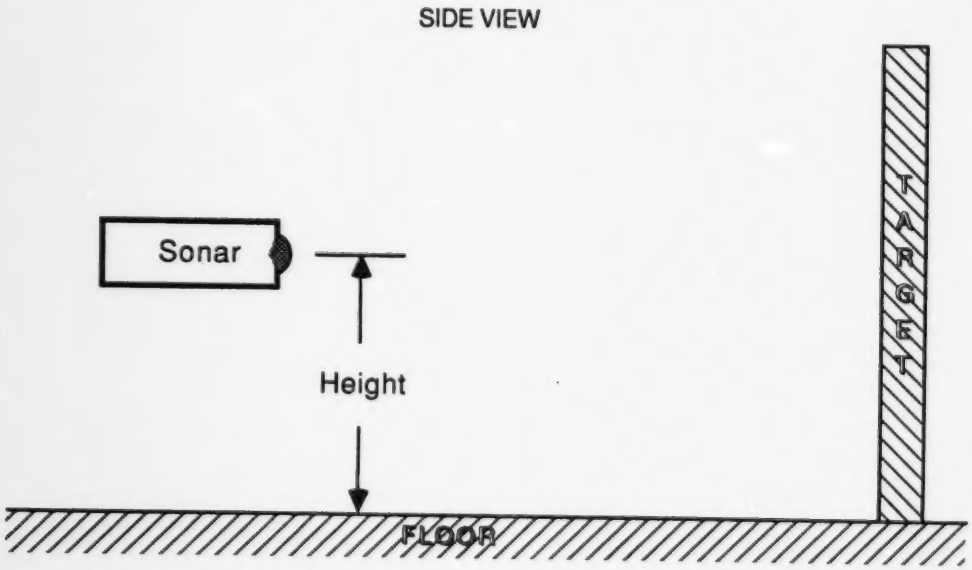
The sonar was positioned to face a flat plywood wall at a distance of 5.5 feet. 100 measurements were taken. The aim of this experiment is to determine how close the readings are to each other when the test conditions are kept fixed.

MEASUREMENTS: Distance to target = 5.5 feet
= 1676 mm

	Count	Count	Count	Count	Count	
1	1929	1930	1930	1924	1930	
2	1923	1925	1905	1923	1920	
3	1928	1923	1925	1923	1928	
4	1931	1922	1921	1933	1922	
5	1924	1931	1929	1922	1924	
6	1928	1923	1933	1923	1932	
7	1924	1923	1923	1928	1919	
8	1923	1931	1935	1930	1928	
9	1923	1932	1924	1924	1931	
10	1931	1923	1926	1926	1931	
11	1924	1918	1931	1932	1930	
12	1924	1900	1922	1930	1924	
13	1924	1919	1932	1920	1927	
14	1927	1930	1933	1927	1930	
15	1926	1923	1923	1923	1925	
16	1925	1932	1930	1923	1931	
17	1924	1923	1921	1924	1930	
18	1931	1930	1925	1930	1928	
19	1929	1916	1924	1933	0051	
20	1922	1923	1924	1924	1928	

Average Count = 1926 (Excluding 99th entry)
= 1661 mm % = 0.9





Test 1.4/ Repeatability

TEST:	2.1 Height

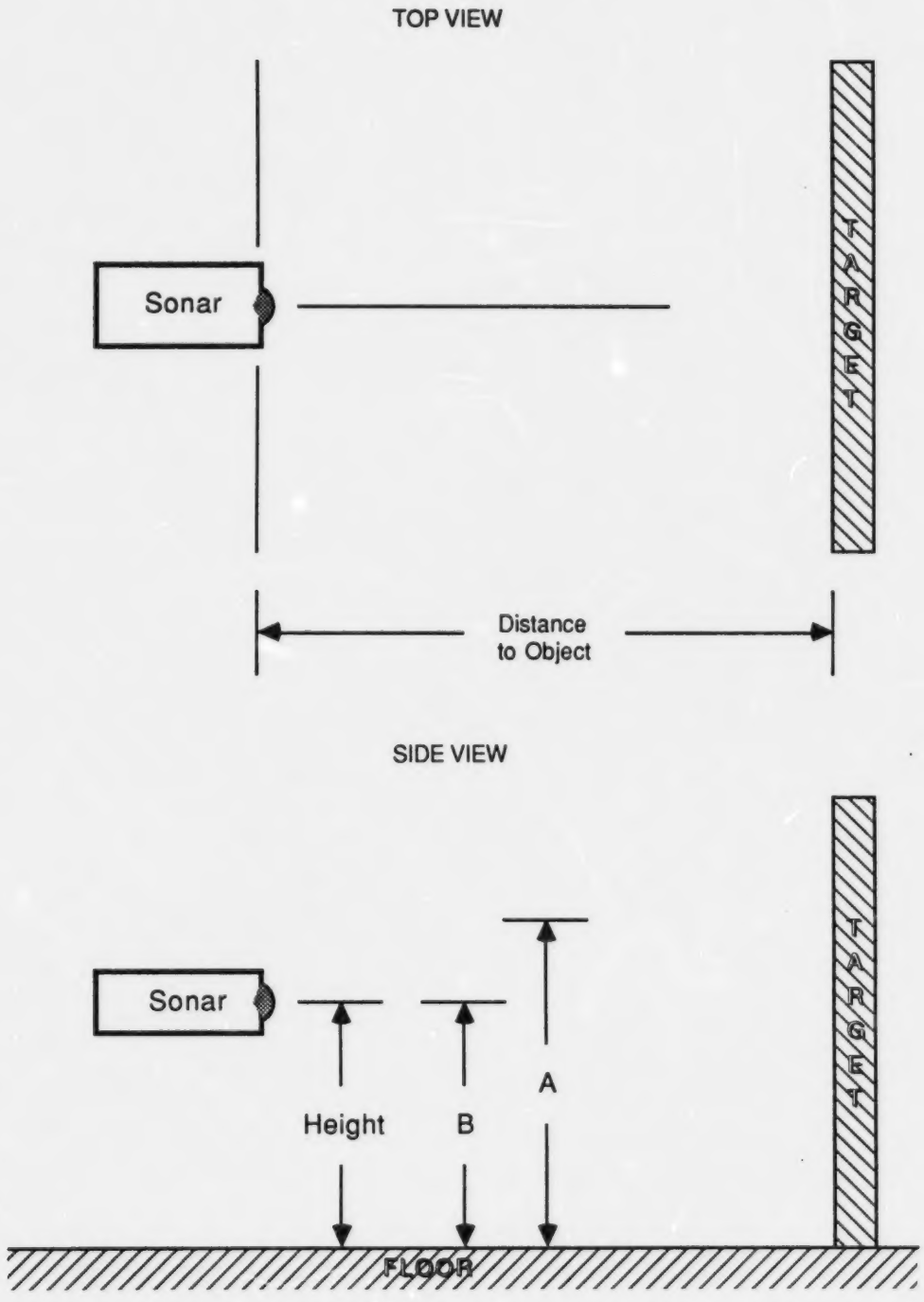
DATE: March 11/86
SENSOR HEIGHT: 660 mm and 260 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a flat plywood wall at Height A. Readings were taken. Then the sonar was moved to Height B. The purpose of this experiment was to see if operation closer to the floor gave noticeable changes in readings.

MEASUREMENTS: A: Height = 660 mm
B: Height = 260 mm

	A	B
	Count	Count
1	2119	2158
2	2119	2179
3	2114	2173
4	2110	2132
5	2108	2150
6	2120	2156
7		2179
8		
9		
10		
Average Count	2115	2161
Average mm	1824	1864



Test 2.1/ Height

TEST: 2.2 Transducer Angle to Reflected Surface

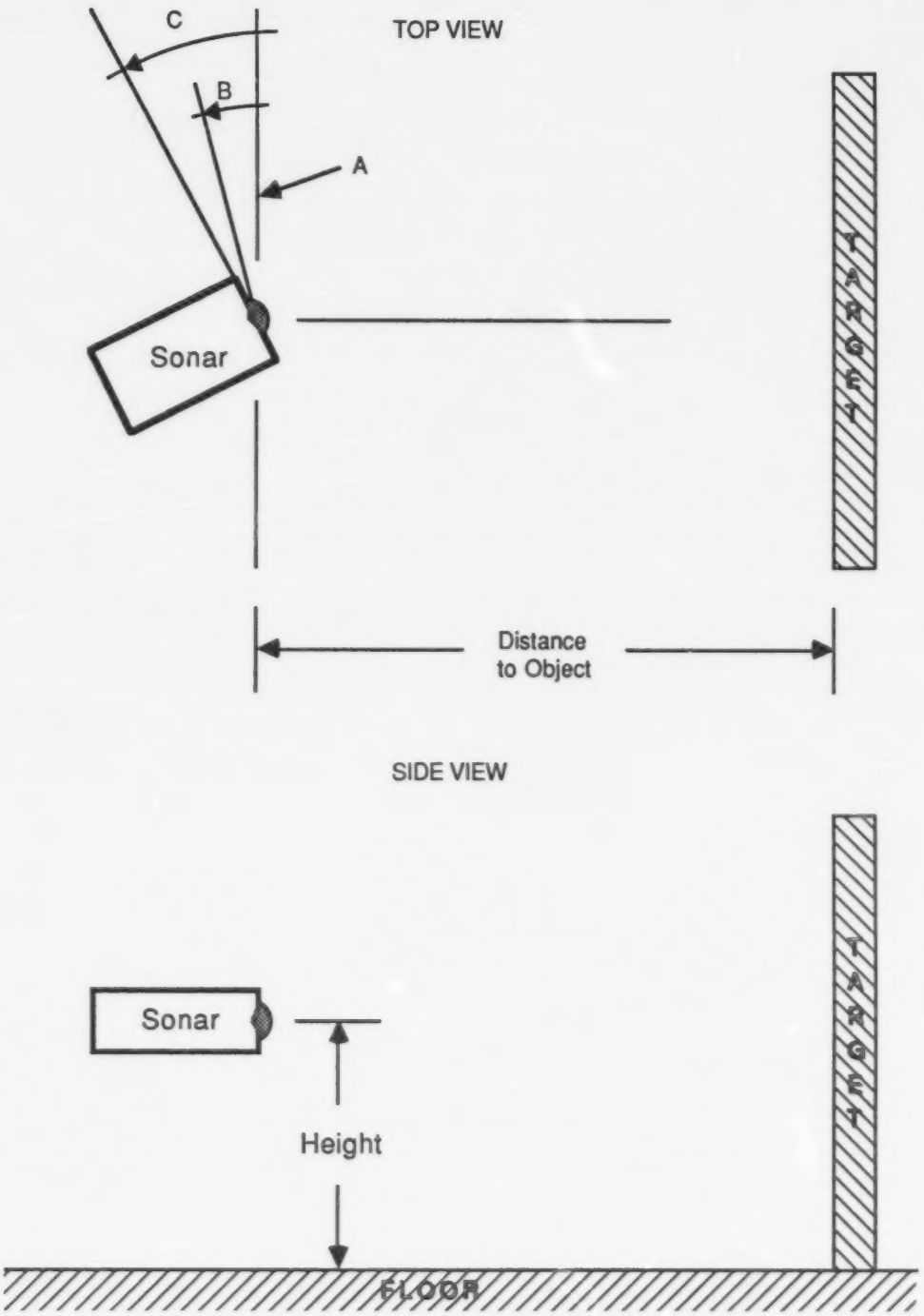
DATE: March 11/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a flat plywood wall in Position A, parallel to the wall. Readings were taken. Then the sonar was moved to Position B at 5.2° to the wall. 10 readings were taken. Then it was placed at an angle of 10.3° to the wall in Position C. The aim of this test was to determine how changing the transducer's position angle to a reflecting surface alters the readings.

MEASUREMENTS: Position A: @= 0 deg
Position B: @= 5.2 deg
Position C: @=10.3 deg

	A	B	C	
	Count	Count	Count	
1	2127	2129	2964	
2	2123	2124	2959	
3	2122	2124	2974	
4	2110	2125	2964	
5	2117	2143	2962	
6		2121	2968	
7		2127	2961	
8		2122	2965	
9		2130	2964	
10		2122	2964	
Average Count	2120	2127	2965	
Average mm	1829	1835	2557	



Test 2.2/ Transducer Angle to Reflected Surface

TEST: 3.1 The Effect of Different Materials

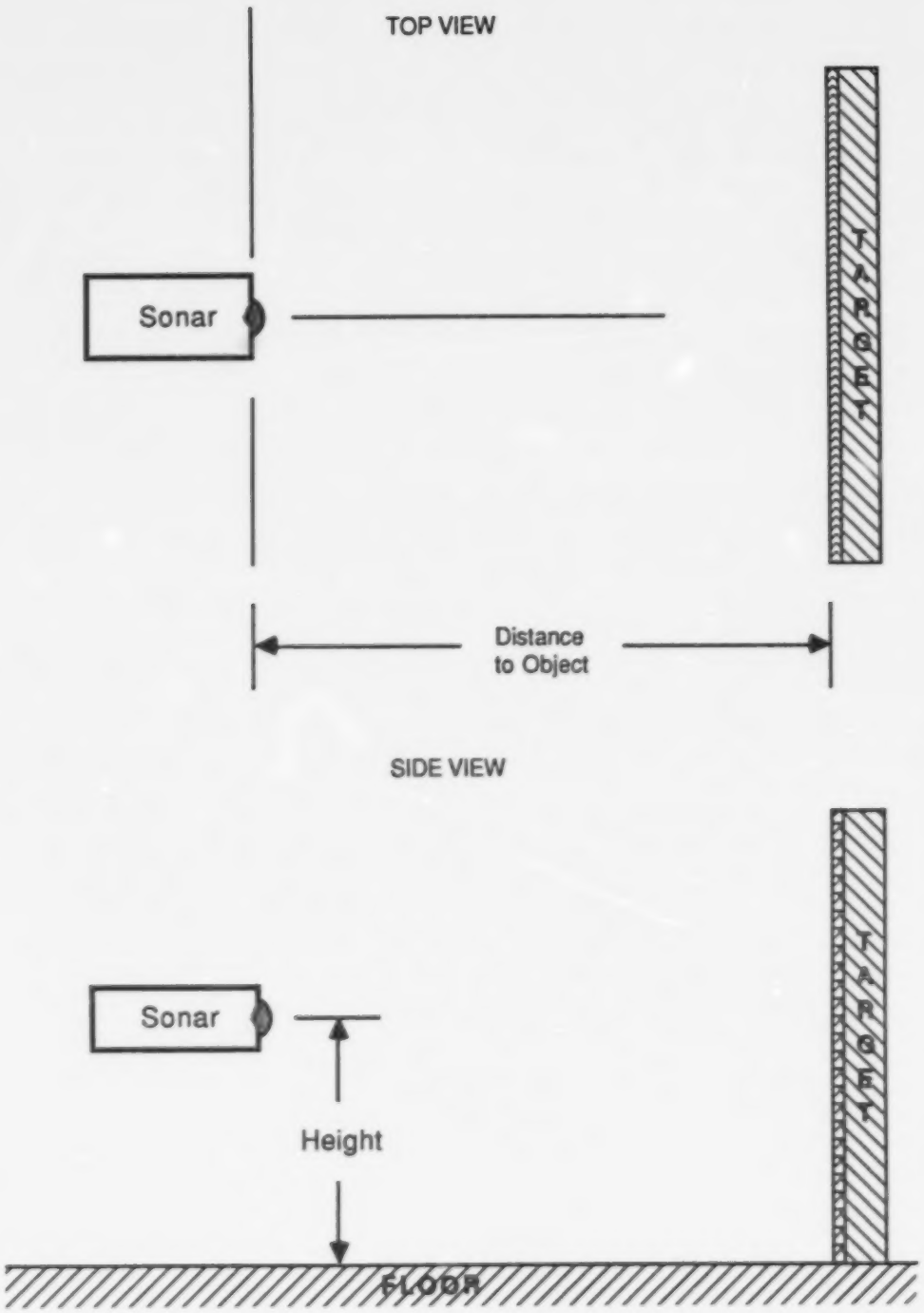
DATE: March 11/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a flat plywood wall, Surface A. 10 readings were taken. Then, the material was changed to surface B and new readings taken. 3 surfaces were tested.

MEASUREMENTS: Surface A: Plywood
Surface B: Metal
Surface C: Glass

	A	B	C	
	Count	Count	Count	
1	2180	2164	2200	
2	2149	2178	2173	
3	2134	2220	2164	
4	2176	2177	2181	
5	2196	2162	2181	
6	2200	2166	2162	
7	2178	2167	2167	
8	2176	2170	2167	
9	2171	2165	2258	
10	2176	2175	2193	
Average Count	2173	2175	2184	
Average mm	1874	1876	1884	



Test 3.1/ The Effect of Different Reflecting Materials

TEST: 3.2 Reflection From Different Objects - Pole

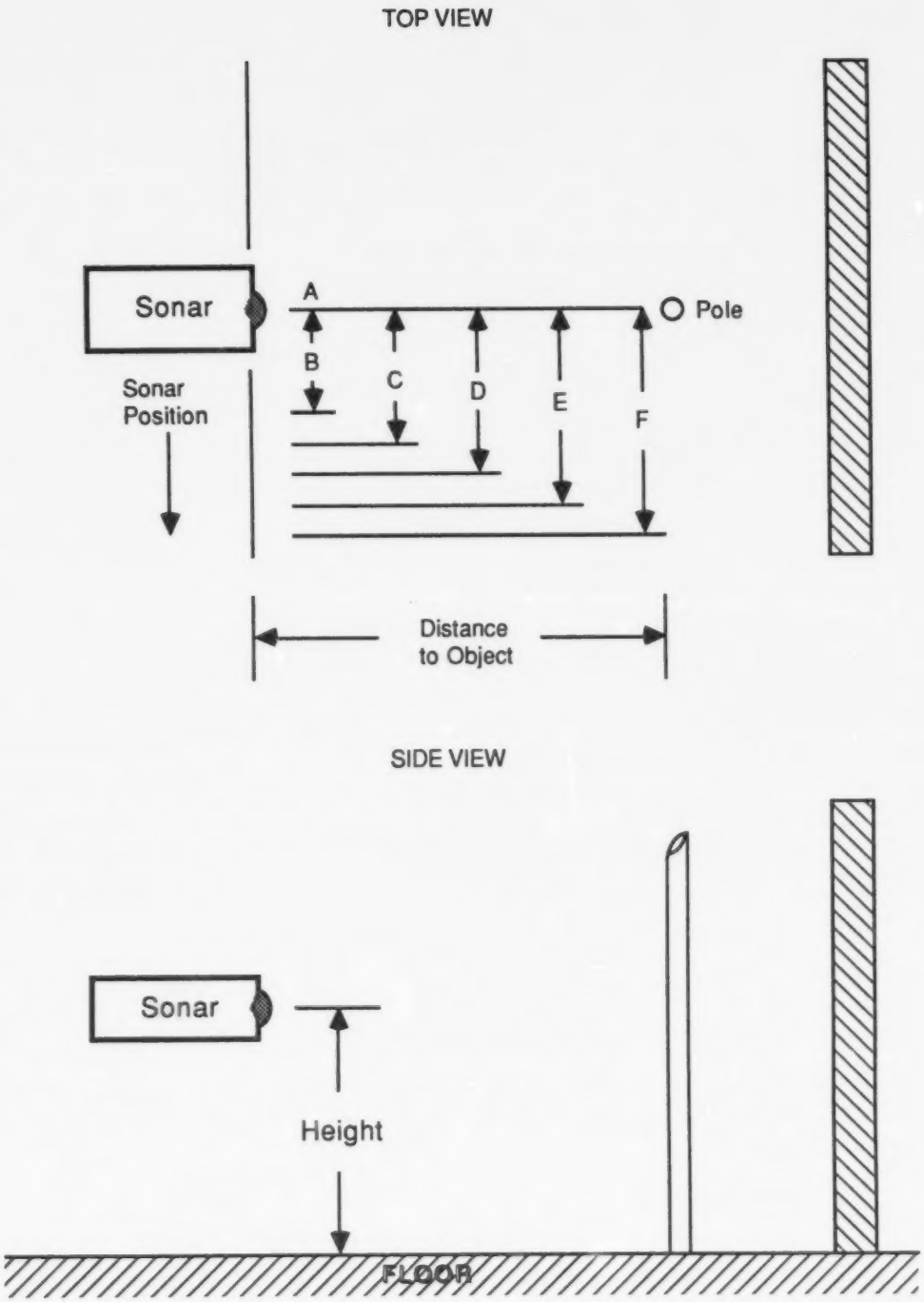
DATE: March 11/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a metal pole in position A. 10 readings were taken. Then the sonar was moved to the left by 10 mm to position B. 10 readings were taken. Then the unit was moved further by another 10 mm to position C and so on.
The purpose of this test was to see if a metal pole could easily be detected.

MEASUREMENTS: Position A: = 0 mm, D: = 50 mm
Position B: = 10 mm, E: = 100 mm
Position C: = 20 mm, F: = 200 mm

	A	B	C	D	E	F
	Count	Count	Count	Count	Count	Count
1	2092	2085	2086	2087	2088	2110
2	2089	2089	2087	2086	2094	2107
3	2075	2089	2086	2086	2093	2106
4	2087	2091	2085	2088	2092	2106
5	2074	2087	2086	2086	2092	2109
6	2090	2093	2086	2087	2091	2107
7	2094	2083	2086	2087	2091	2103
8	2086	2082	2086	2088	2091	2102
9	2088	2078	2088	2086	2091	2103
10	2092	2088	2086	2086	2095	2106
Average Count	2087	2087	2086	2087	2092	2106
Average mm	1800	1800	1799	1800	1804	1816



Test 3.2/ Reflection from Different Objects - Pole

TEST:	3.3 Reflection from a Narrow Surface

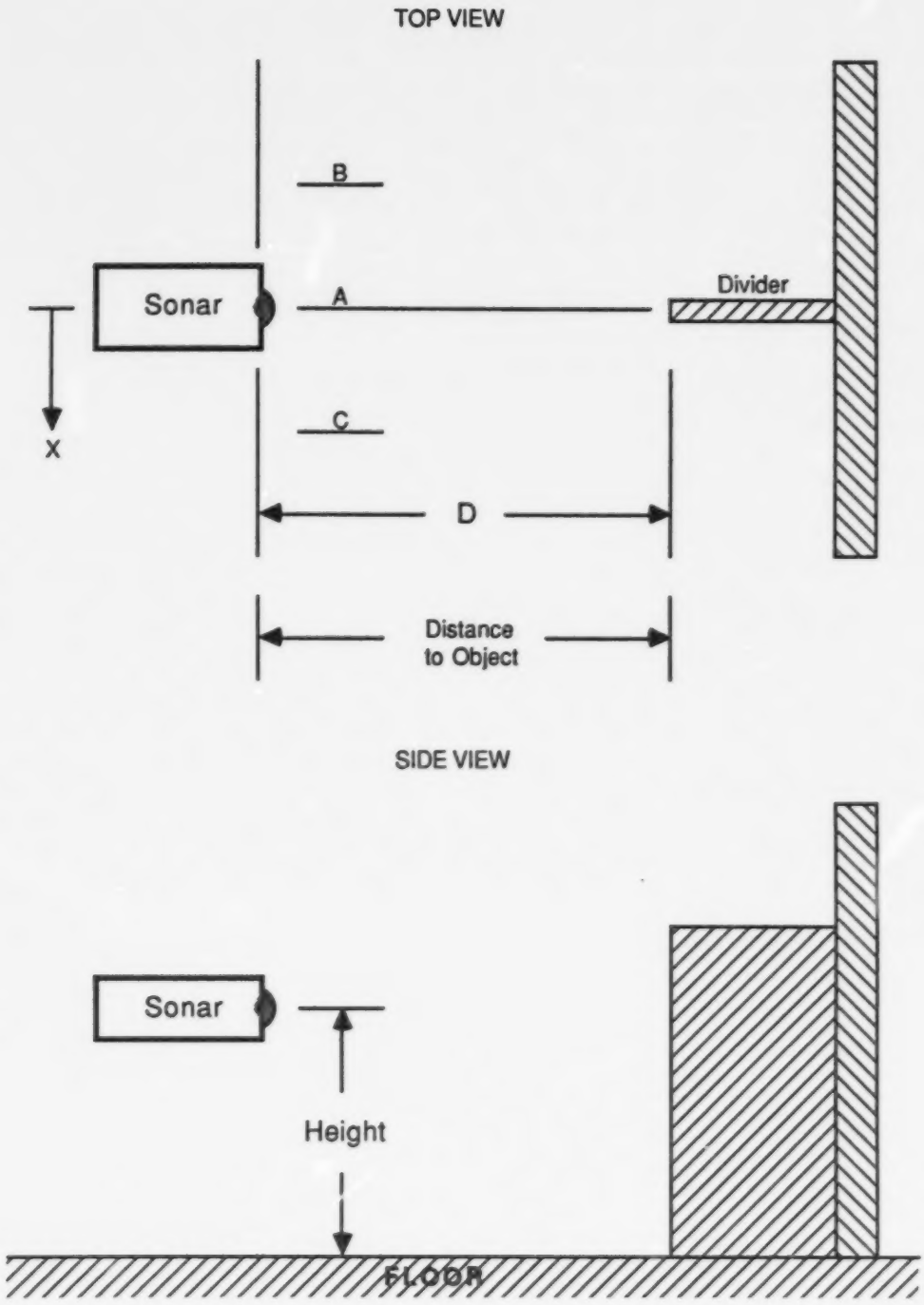
DATE: March 11/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a narrow divider in position A. 10 readings were taken. Then the sonar was moved to the left by 200 mm to position B. 10 readings were taken. Then the unit was moved to the right by 200 mm to position C. The aim of this test was to see if the unit detects a narrow surface.

MEASUREMENTS: Position A: X = 0 mm, D = 2134 mm
Position B: X = -200 mm, D = 2134 mm
Position C: X =+200 mm, D = 2134 mm

	A	B	C	
	Count	Count	Count	
1	2439	2466	2454	
2	2439	2458	2450	
3	2439	2459	2451	
4	2438	2458	2450	
5	2439	2458	2452	
6	2441	2471	2450	
7	2440	2460	2450	
8	2441	2471	2450	
9	2441	2458	2452	
10				
Average Count	2440	2462	2451	
Average mm	2105	2124	2114	
%	1.4			



Test 3.3/ Reflection from a Narrow Surface

TEST: 4.1 Beam Width

DATE: March 11/86
SENSOR HEIGHT: About 1 m
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a flat plywood wall. Slowly, paper sheets on extensions were brought toward the beam, one from each side. When the sonar detected each sheet, all distances were recorded.
The aim of this experiment was to measure the Beam Width.

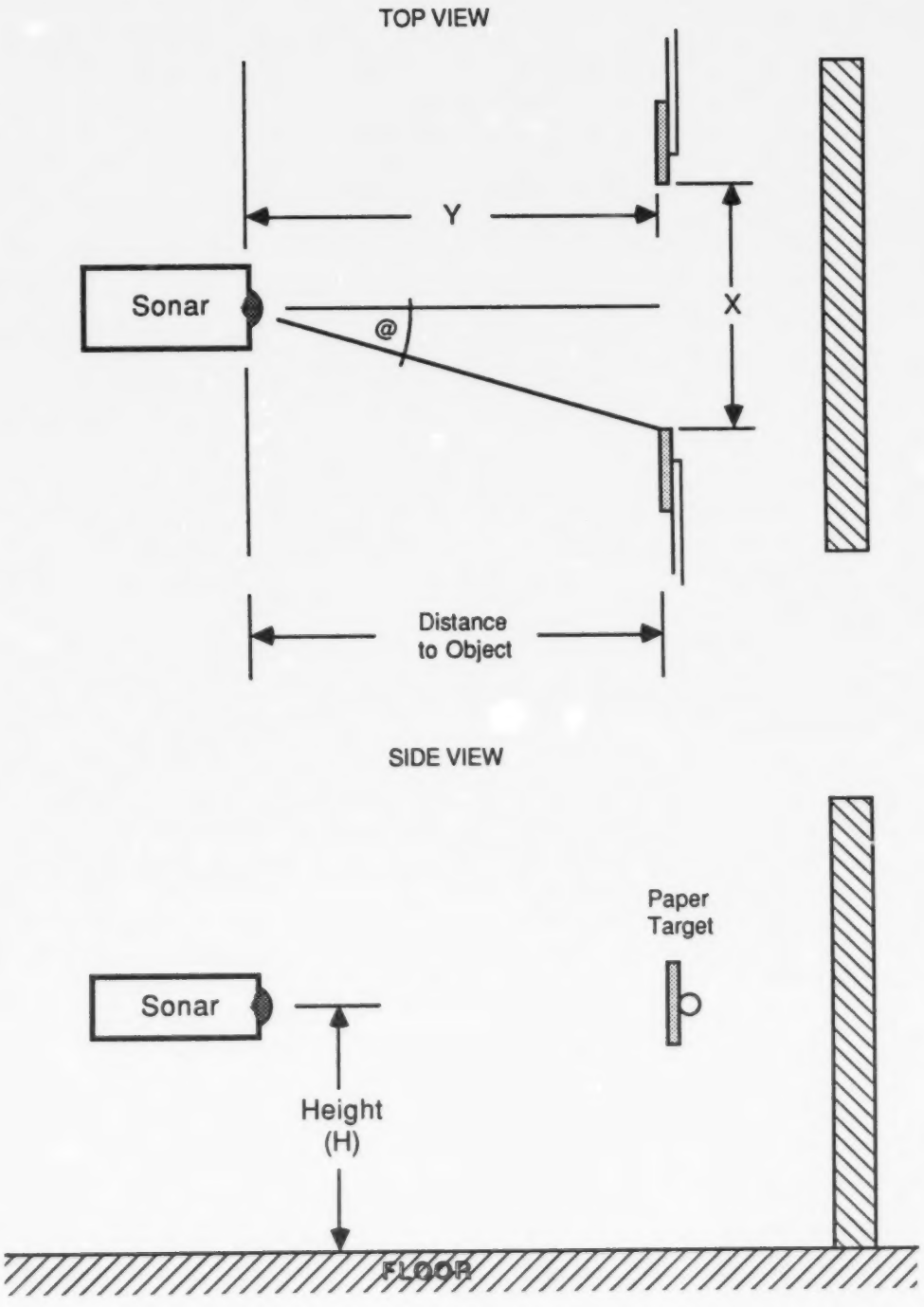
MEASUREMENTS:

Distance X = 317 mm
Distance Y = 1829 mm

@ = ARCTAN 317/1829
= 9.85 degrees

BEAM WIDTH = 2 x @
= 2 x 9.85

= 19.7 degrees



Test 4.1/ Beam Width

TEST: 5.1 Interference between 2 Units

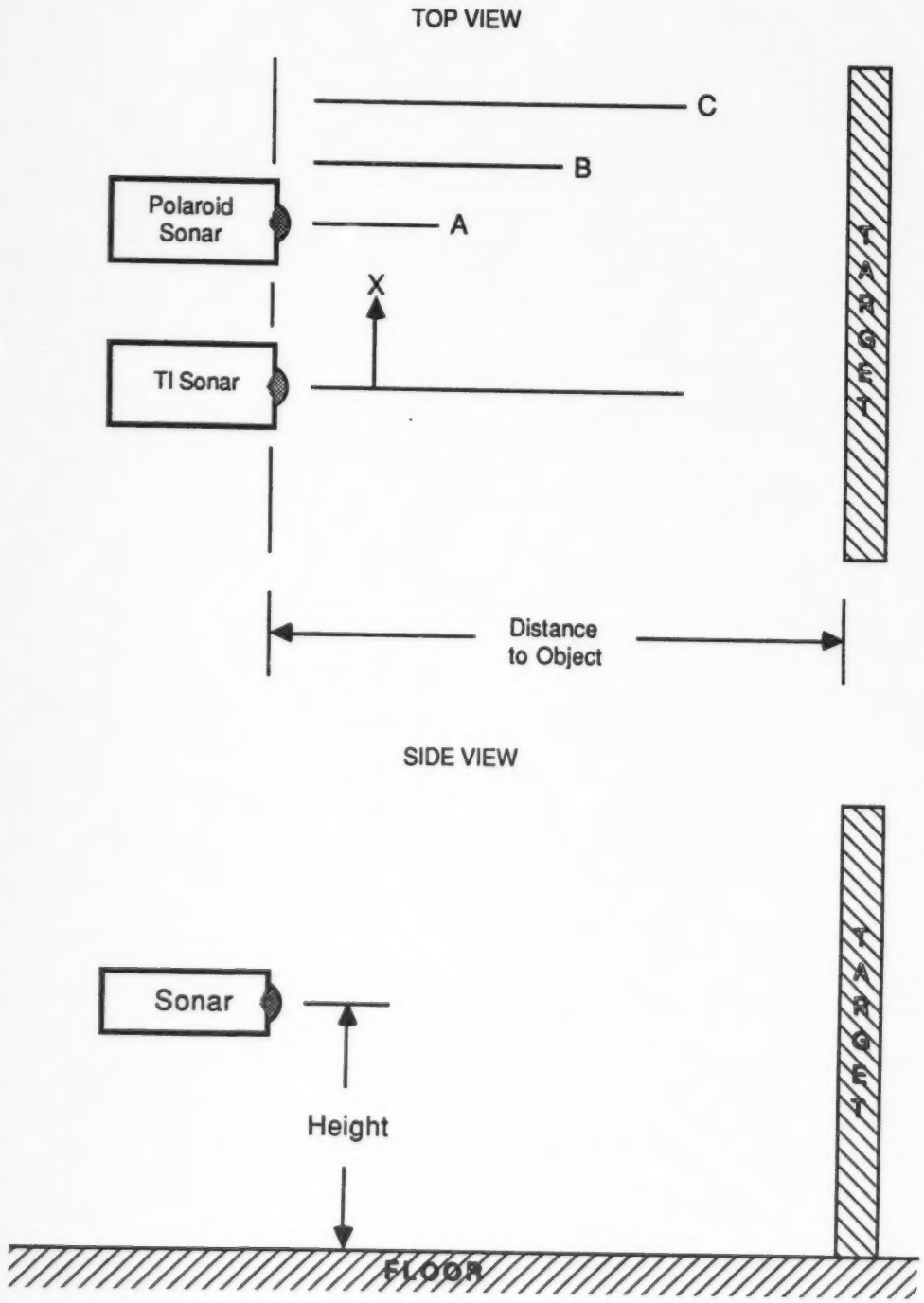
DATE: March 11/86
SENSOR HEIGHT: 660 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Manual

DESCRIPTION:

The sonar was positioned to face a flat plywood wall. A second sonar unit (Polaroid) was placed in position A, a set spacing X beside the first. Readings were taken initially with the second unit off, then with the second unit on. The second unit was taking measurements about 20 times a second.
Then this was repeated with a different spacing X.

MEASUREMENTS: Position A: X = 200 mm
Position B: X = 400 mm
Position C: X = 600 mm

	A		B		C	
Unit 2	OFF	ON	OFF	ON	OFF	ON
	Count	Count	Count	Count	Count	Count
1	2111	2106	2111	2094	2112	900
2	2109	765	2146	2156	2120	2110
3	2107	2184	2109	2109	2110	1648
4	2109	2131	2093	1877	2111	2115
5	2112	2111	2125	2100	2120	1651
6	2110	2110	2182	1388	2114	1338
7	2131	496	2139	2147	2122	2105
8	2109	2110	2183	1657	2110	2156
9	2116	711	2156	2127	2119	2122
10			2121	1073	2143	2144
Average Count	2113	1639	2136	1873	2118	1828
Average mm	1822	1414	1842	1616	1827	1577



Test 5.1/ Interference Between 2 Units

SECTION 2
March 17 to March 24

REPEATABILITY

The previous tests show that even when test conditions remain the same, sequential results often vary up to 30 counts. To be useful in a guidance system, the repeatability of measurements must be much better than this, deviating by no more than 4 or 5 counts.

EXAMINATION OF THE SIGNALS

To gain further insight, selected signals in the test setup were examined with an oscilloscope. Figure A2 shows the test setup, which is identical to Figure A1, with the exception of the oscilloscope and microphone.

The 50 kHz echo picked up by the transducer is very weak. Without filtering, this can not be seen at the transducer's output while mixed in with the ambient noise. For this reason, a microphone sensitive in the 50 kHz region was used to detect the echo.

Auto mode was used; thus, measurements were being initiated every second.

RESULTS

The following series of figures show the results of this examination (refer to Figure A1 for signal names):

Figure A3. Signal: XMIT

The signal being sent by the transducer. 16 pulses at 50 kHz.

Figure A4. Signal: XMIT

Expanded from Figure A3. The signal being sent by the transducer. 16 pulses at 50 kHz.

Figure A5. Signal: XMIT

The signal being sent by the transducer. 16 pulses at 50 kHz. Two successive transmissions.

Figure A6. Signal: XMIT and MIC

Graph 1 shows XMIT 6 ms from the transmission, which is when the echo has returned. As expected, the echo is too weak to be observed without filtering. MIC (Graph 2) is the signal picked up at the same time from a microphone sensitive to 50 kHz and placed beside the transducer.

Figure A7. Signal: ECHO and MIC

30 samples of ECHO superimposed on each other (Graph 1). MIC is shown on Graph 2.

Figure A8. Signal: ECHO and MIC

30 samples of ECHO superimposed on each other (Graph 1). MIC is shown on Graph 2.

Figure A9. Signal: ECHO and MIC

30 samples of ECHO superimposed on each other (Graph 1). MIC is shown on Graph 2. Expanded in time from Figures A7 and A8.

Figure A10. Signal: XMIT and INIT

Graph 1 shows XMIT, and Graph 2 shows INIT at the same time.

Figure A11. Signal: XMIT and INIT

Same as Figure A10, only with 30 samples superimposed on each other.

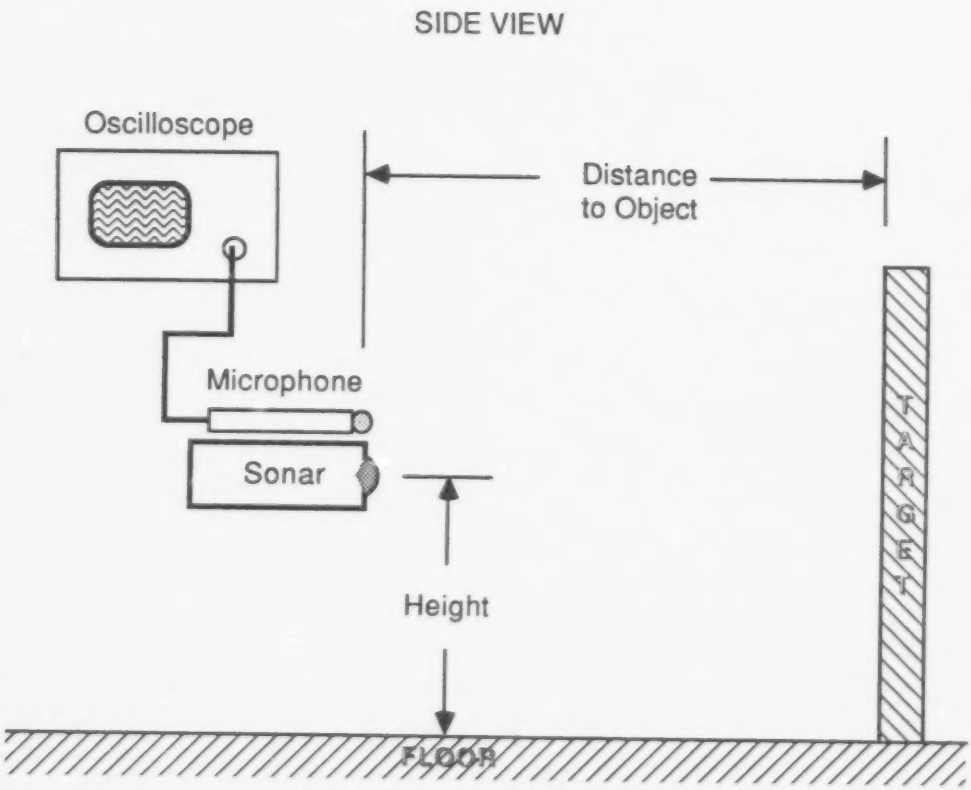


Figure A2/ Experimental Setup (March 17)

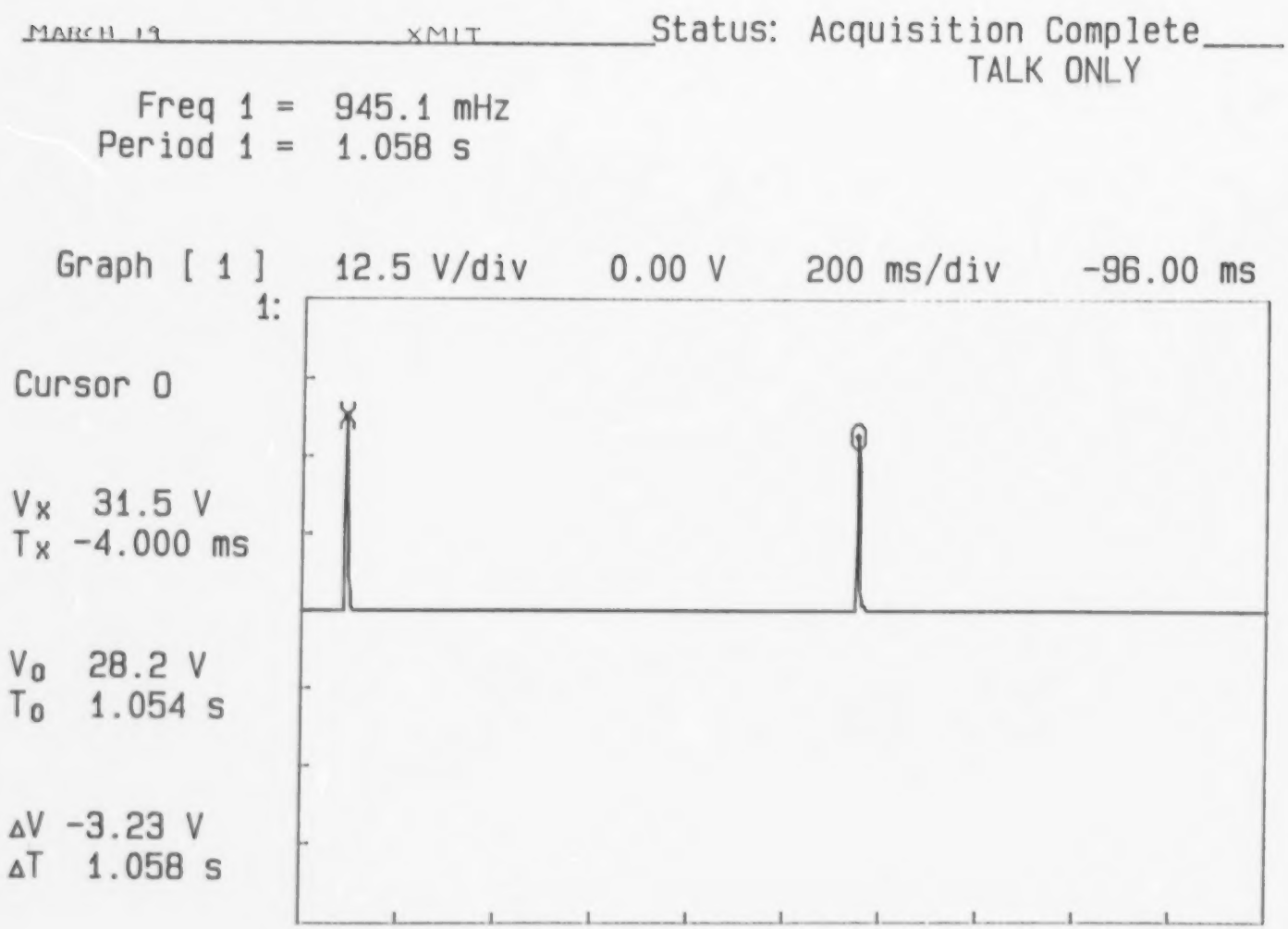


Figure A3/ XMIT (March 19)

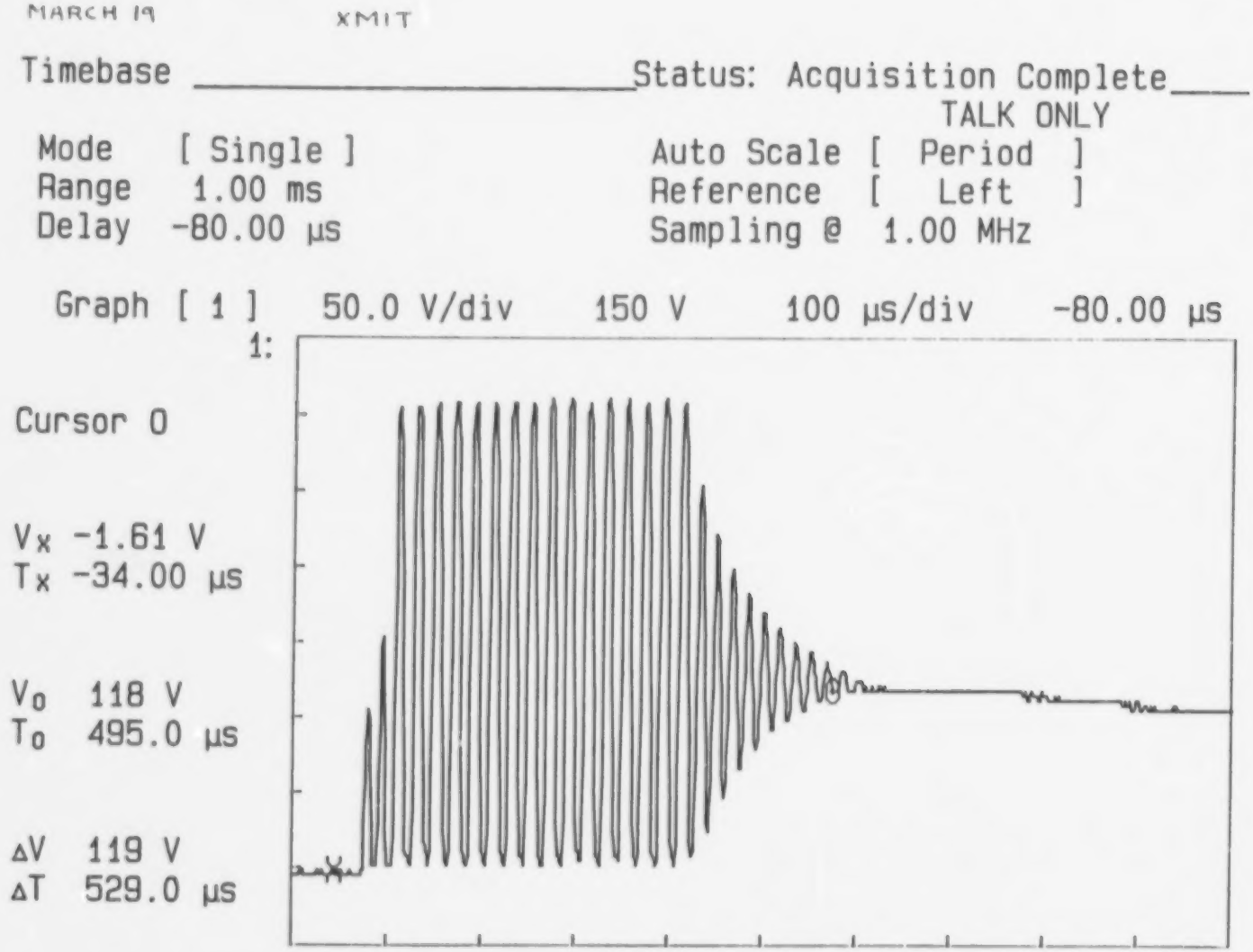


Figure A4/ XMIT (March 19)

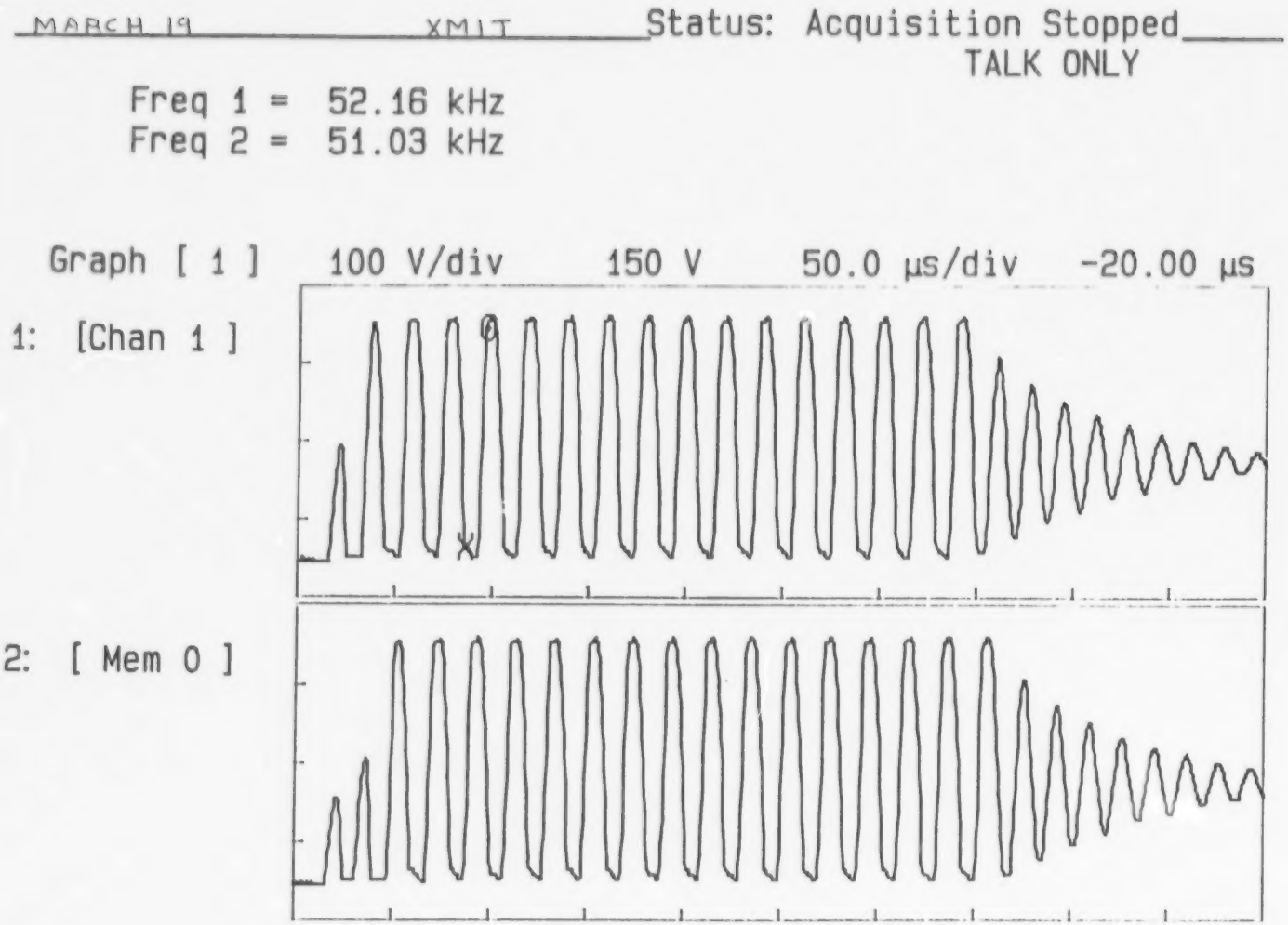


Figure A5/ XMIT (March 19)

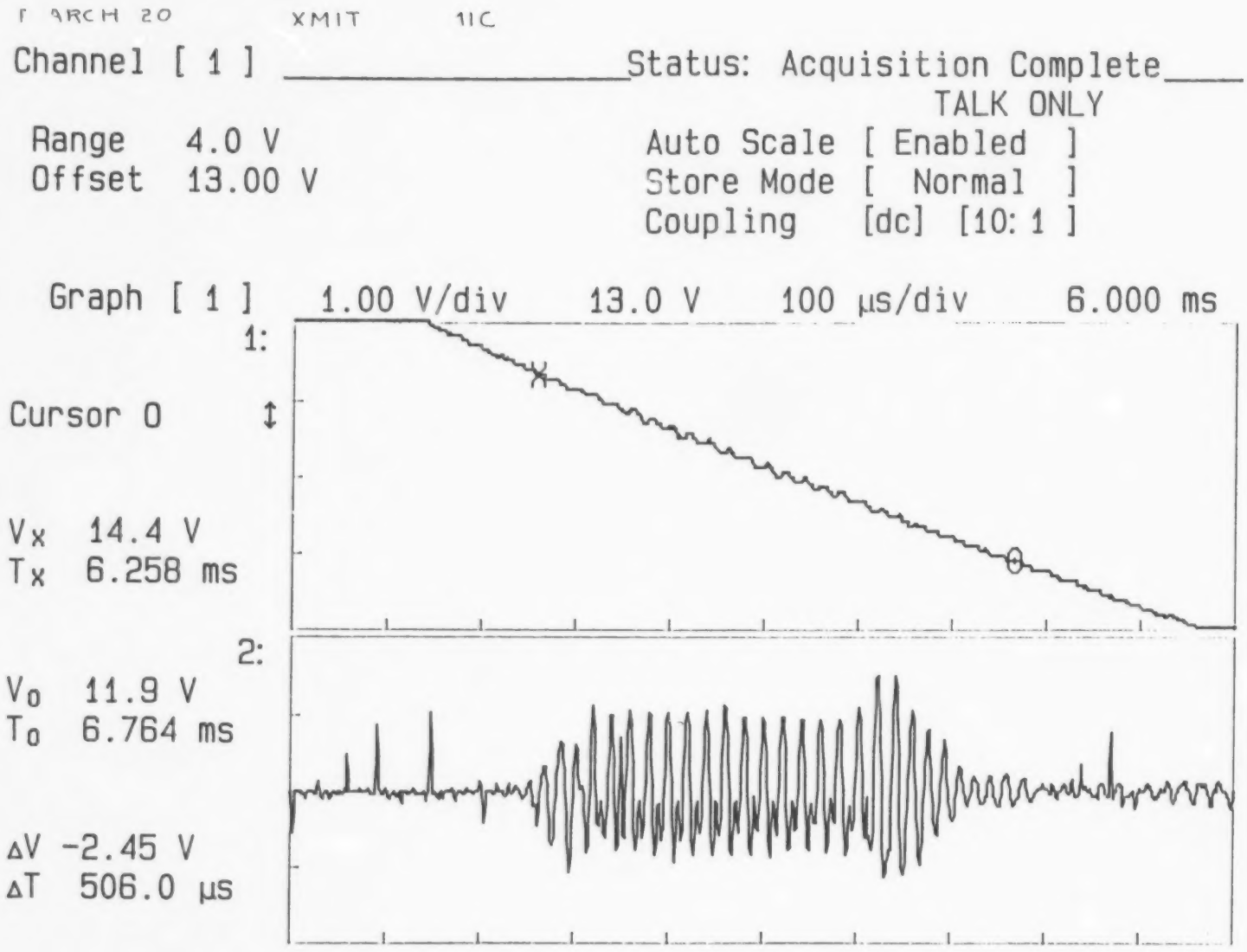


Figure A6/ XMIT and MIC (March 20)

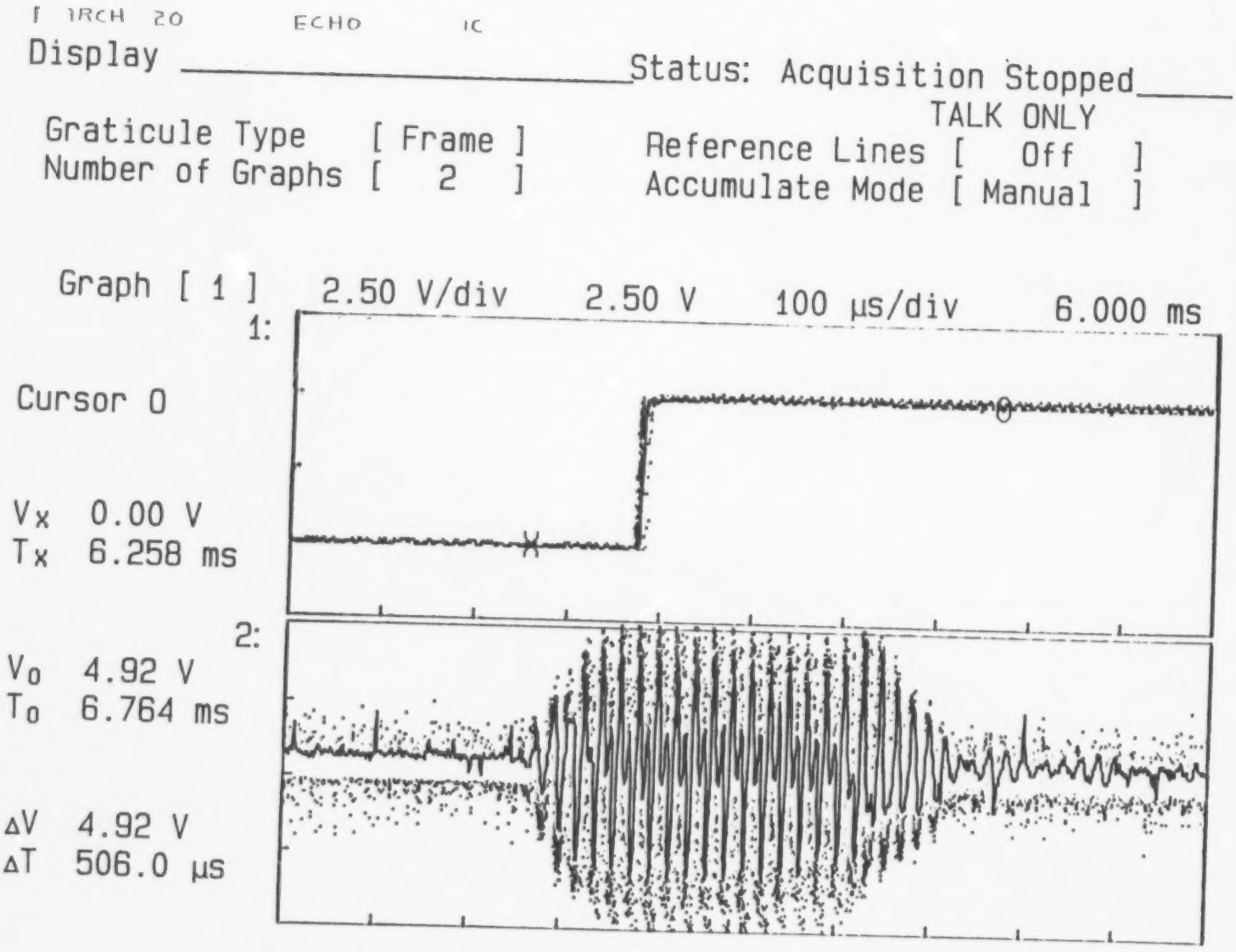


Figure A7/ ECHO and MIC (March 20)

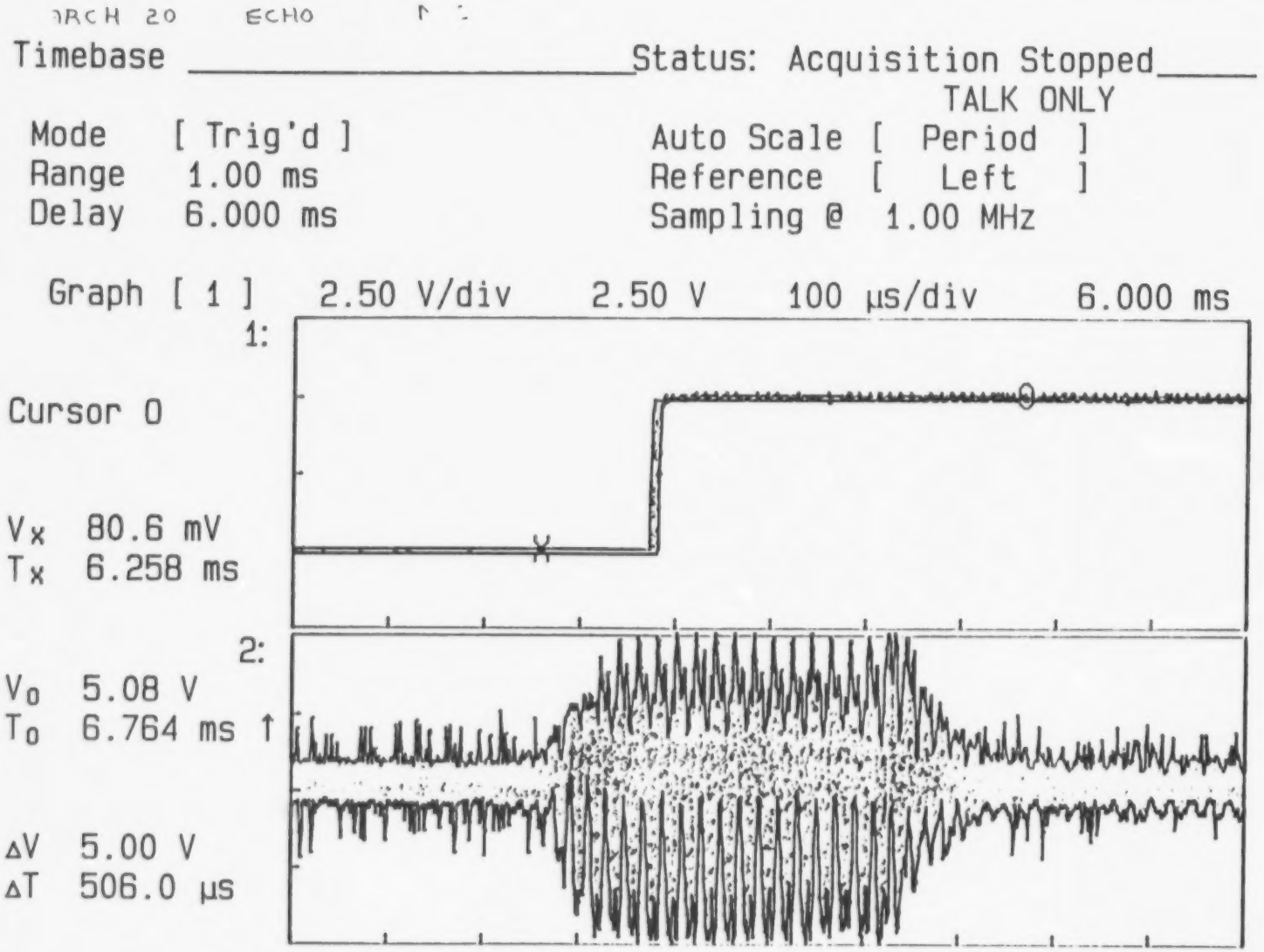


Figure A8/ ECHO and MIC (March 20)

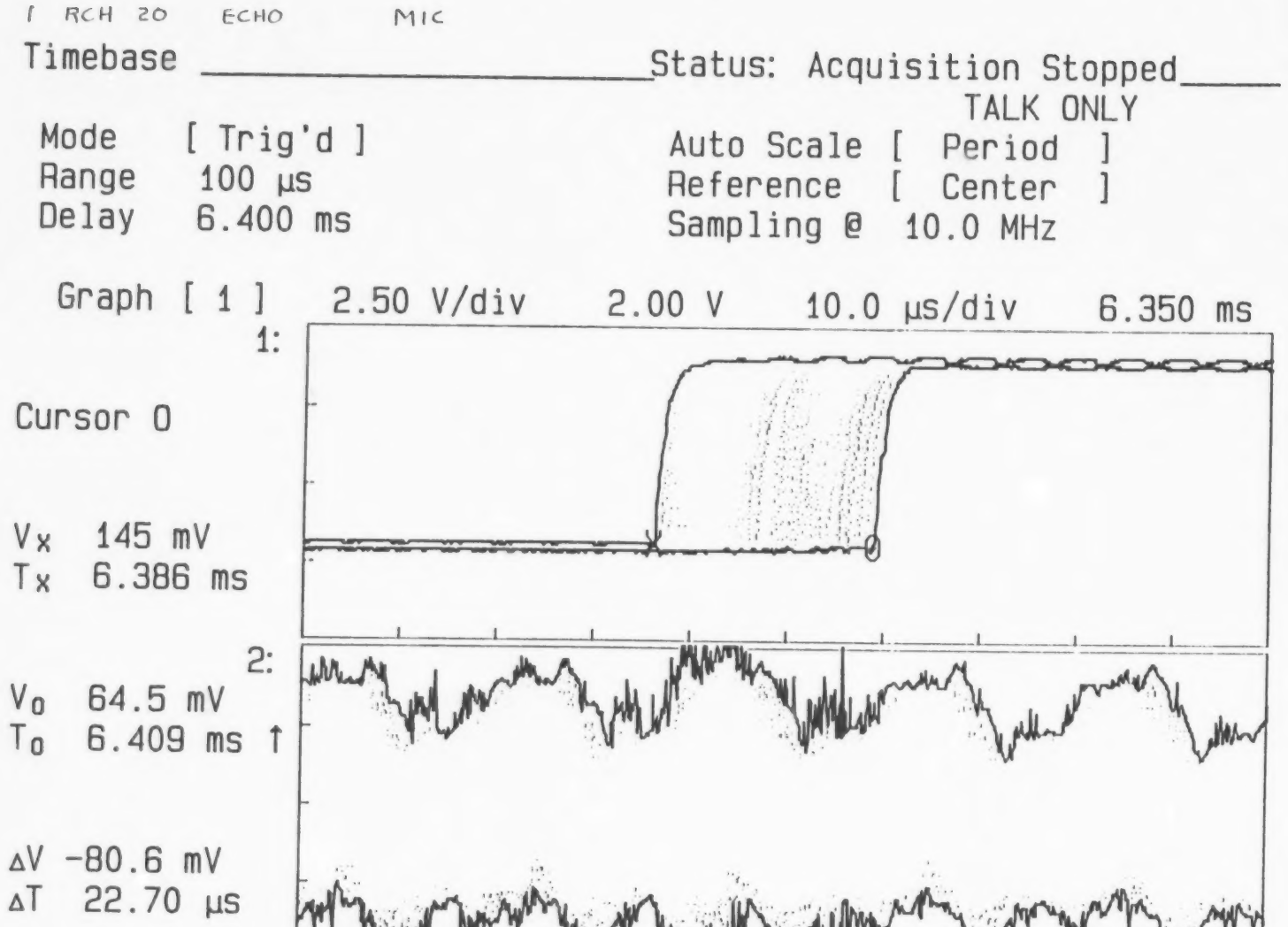


Figure A9/ ECHO and MIC (March 20)

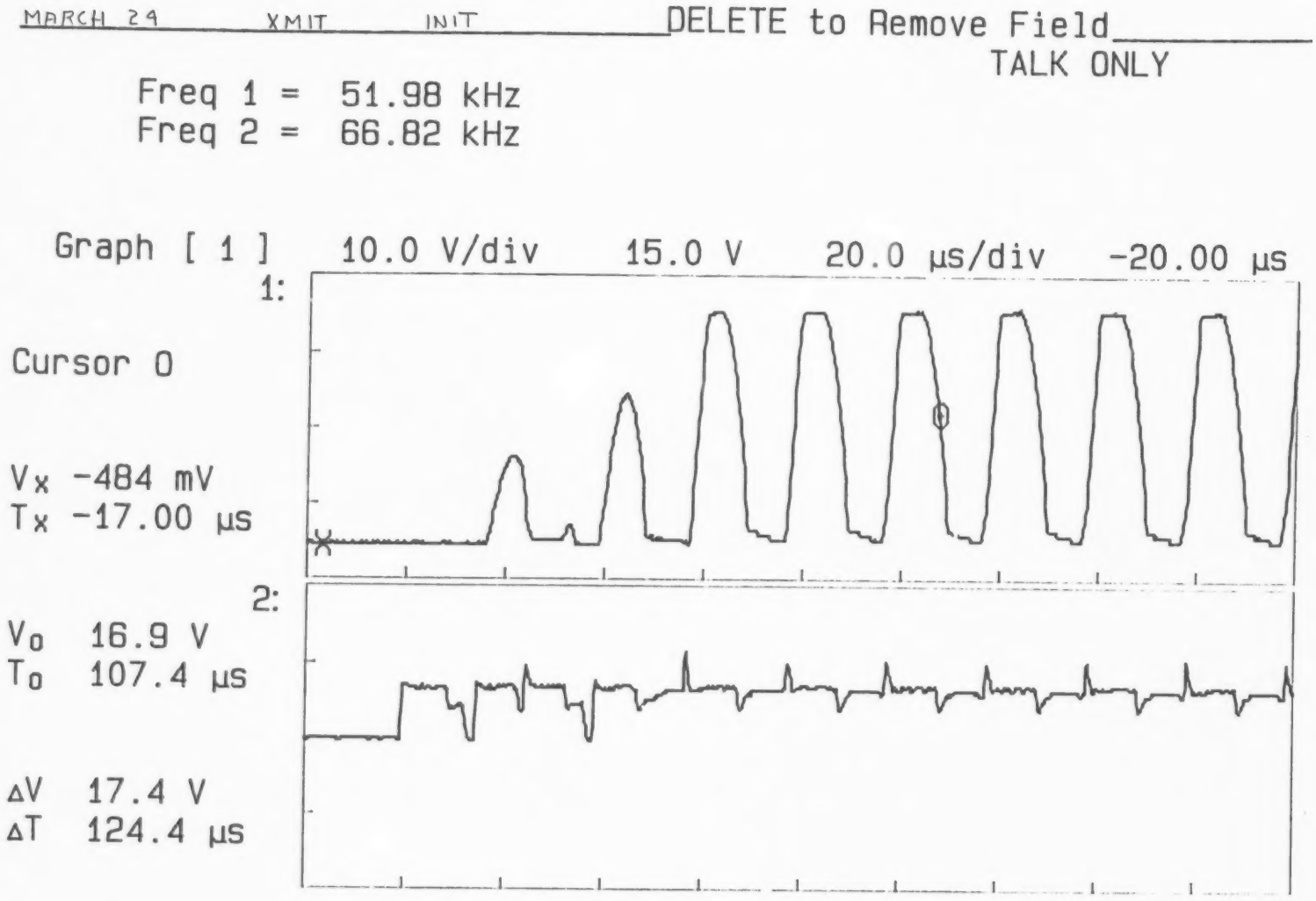


Figure A10/ XMIT and INIT (March 24)

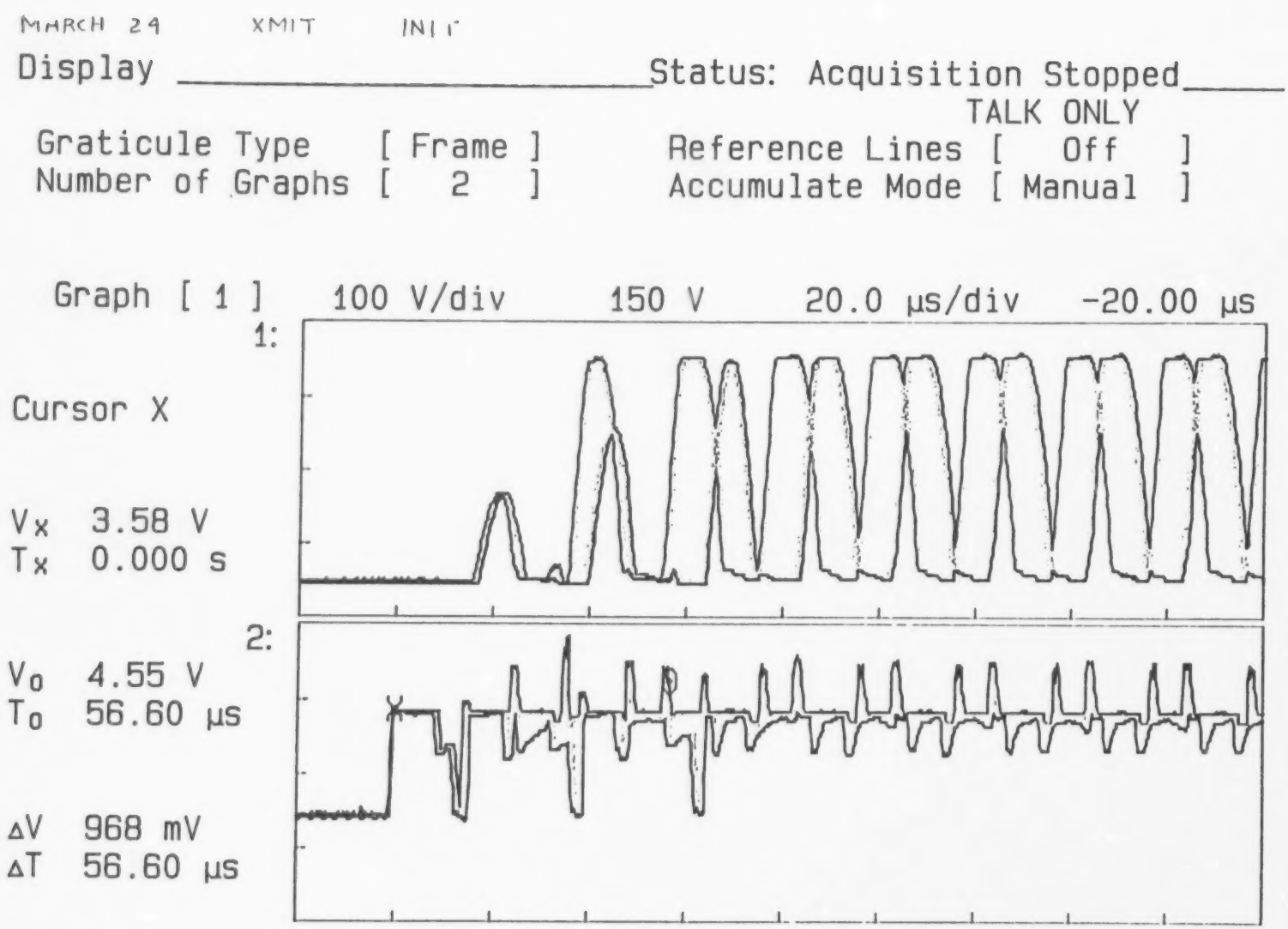


Figure A11/ XMIT and INIT (March 24)

OBSERVATIONS

The Graphs indicate that
- INIT is picking up a substantial amount of noise during transmission;
- ECHO is brought high at different times, which vary by about 25 μs;
- One or two small pulses are generated previous to the transmission of the 16 pulses at 50 kHz.

CORRECTIONS

To reduce noise picked up during transmission, the INIT line was buffered from the rest of the circuit, using some inverters, as shown in Figure A12.

RESULTS

Figure A13. Signals: INIT and COUNT

INIT was again examined on the oscilloscope and is shown in Figure A14. Some noise has been reduced (Graph 1).

COUNT is the signal that is patched through to the counter. It is shown on Graph 2 and is seen to contain some noise.

Test 1.4 was done again to see if repeatability was improved. It was done both before and after the buffers were added.

FURTHER CORRECTIONS

To further reduce noise, separate power supplies were used, as shown in Figure A14. One was for the TI board, and a separate one was used for the rest of the circuitry.

RESULTS

Figure A15. Signal: INIT and COUNT

ECHO and COUNT were observed on the scope. Very little noise is present now.

Figure A16. Signal: ECHO

The ECHO signal now varies by only a few microseconds

The repeatability test was run again.

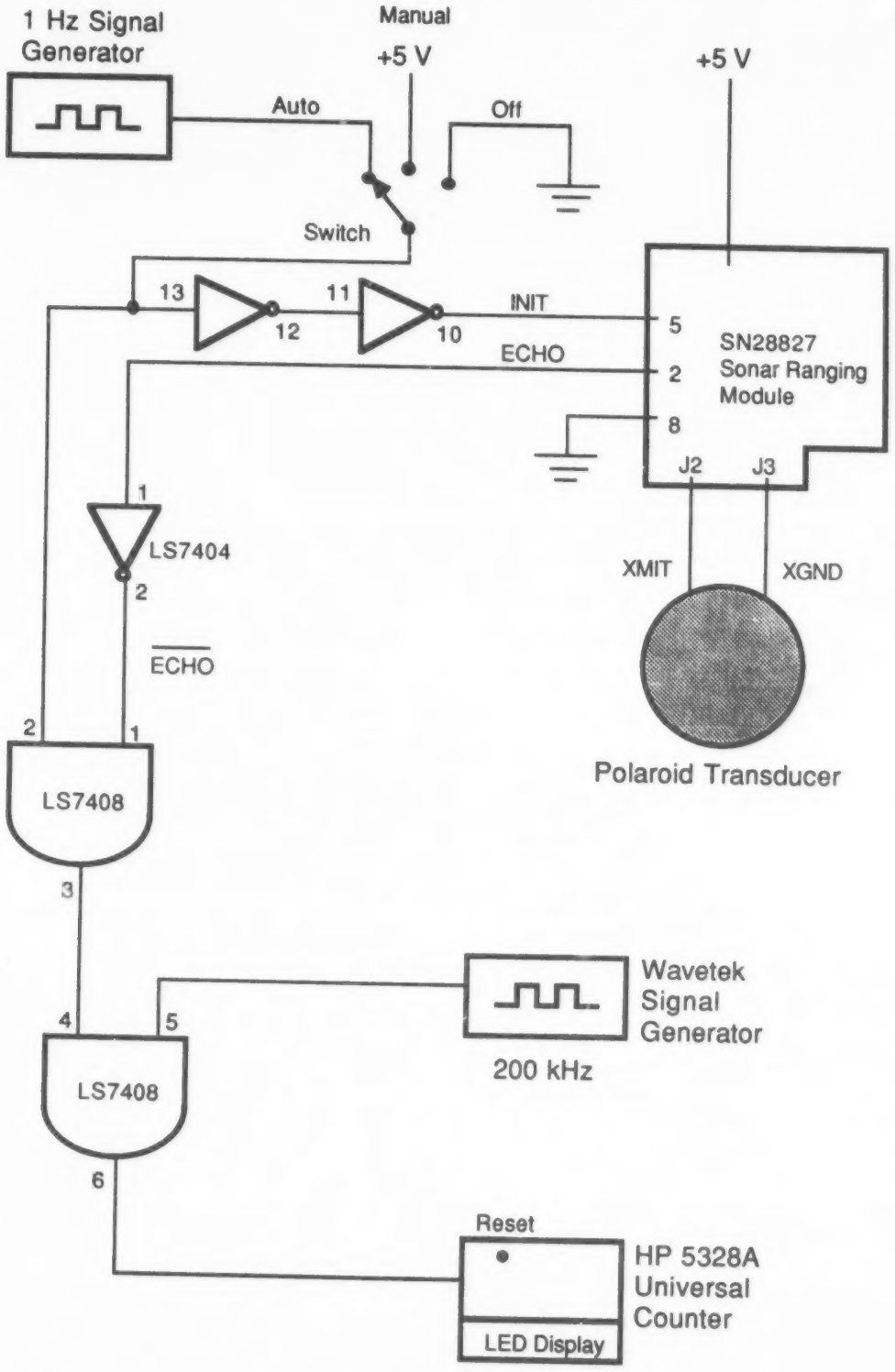


Figure A12/ Experimental Setup – Addition of Buffers (March 24)

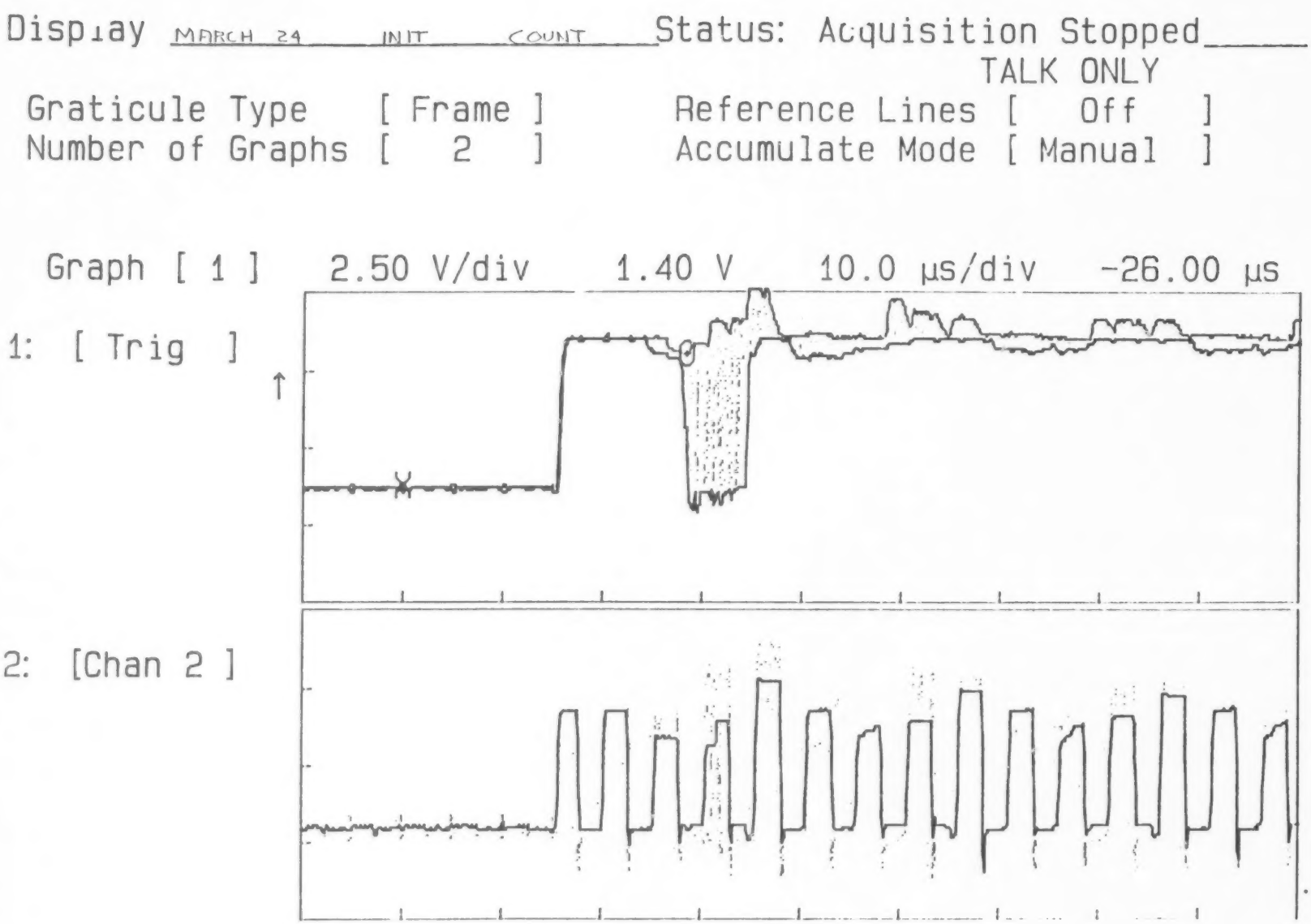

Display MARCH 24 INIT COUNT
Status: Acquisition Stopped
TALK ONLY
Graticule Type [Frame]
Reference Lines [Off]
Number of Graphs [2]
Accumulate Mode [Manual]
Graph [1] 2.50 V/div 1.40 V 10.0 µs/div -26.00 µs
1: [Trig]
2: [Chan 2]

Figure A13/ INIT and COUNT (March 24)

TEST: 1.4 Repeatability

DATE: March 24/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall at a distance of 1486 mm. Two tests were done. First, Figure A1. was used (No buffers added) and then Figure A12 was used which includes the buffering. 25 measurements were taken. The aim of this test is to see how repeatable the readings are in each case.

MEASUREMENTS:

	1) With No Buffers added		
	Count	Count	Count
1	1637	1640	1627
2	1630	1642	1633
3	1626	1636	1637
4	1636	1623	1626
5	1630	1631	1619
6	1640	1625	
7	1639	1620	
8	1634	1632	
9	1632	1640	
10	1626	1635	

	2) With Buffers Added		
	Count	Count	Count
1	1618	1618	1617
2	1618	1617	1619
3	1618	1617	1618
4	1618	1618	1618
5	1618	1618	1618
6	1618	1617	
7	1618	1618	
8	1618	1617	
9	1617	1617	
10	1618	1617	

TEST: 1.4 Repeatability

DATE: March 24/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

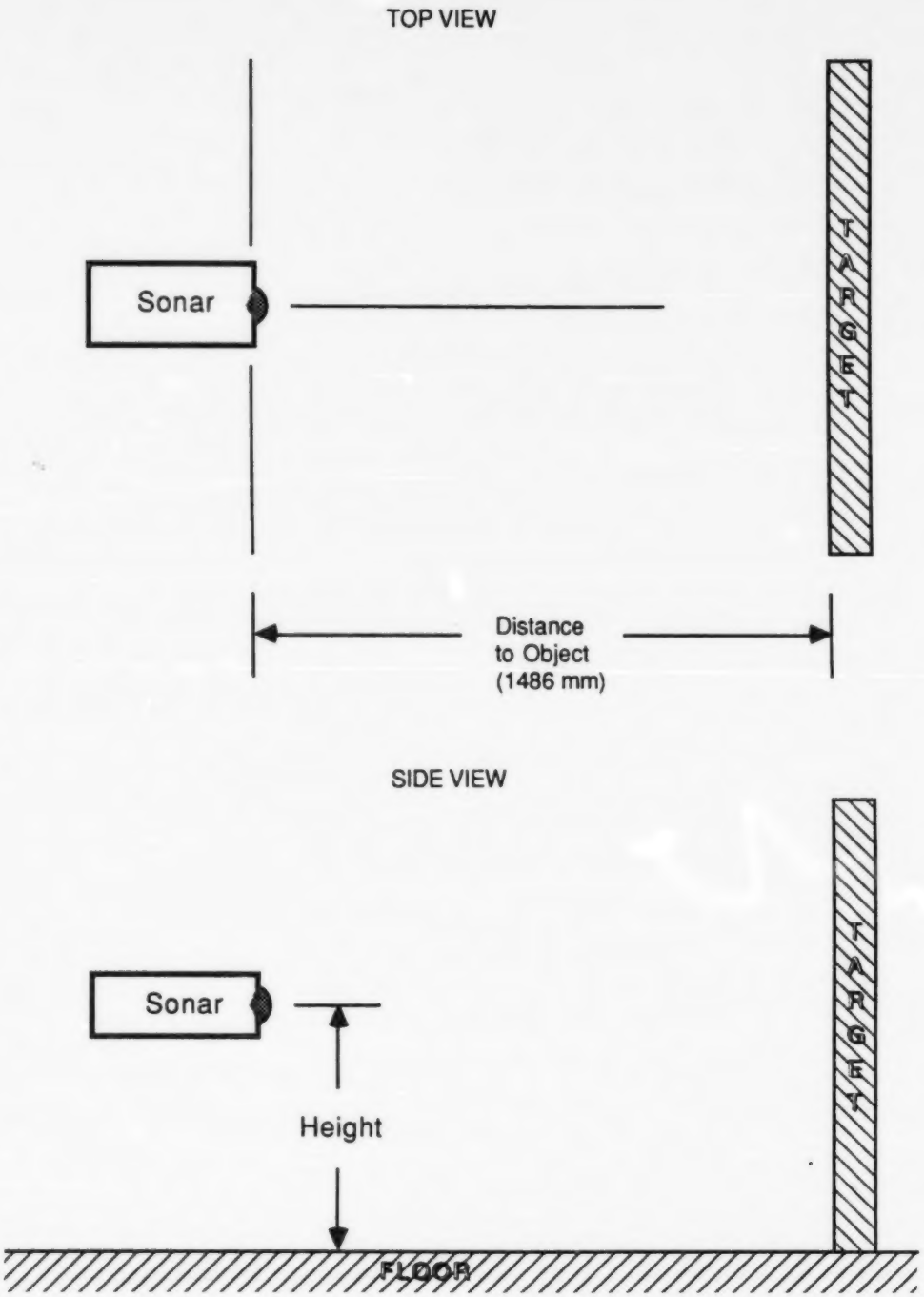
The sonar was positioned to face a flat plywood wall at a distance of 1486 mm. The circuit was that of Figure A14 (Buffers added, separate power supplies)

MEASUREMENTS:

	Count	Count	Count		
1	1617	1618	1617		
2	1618	1617	1617		
3	1617	1617	1617		
4	1618	1617	1617		
5	1618	1617	1617		
6	1618	1617			
7	1617	1617			
8	1617	1617			
9	1617	1617			
10	1617	1617			

Average Count = 1617
= 1394 mm

% = 6.1



Test 1.4/ Repeatability

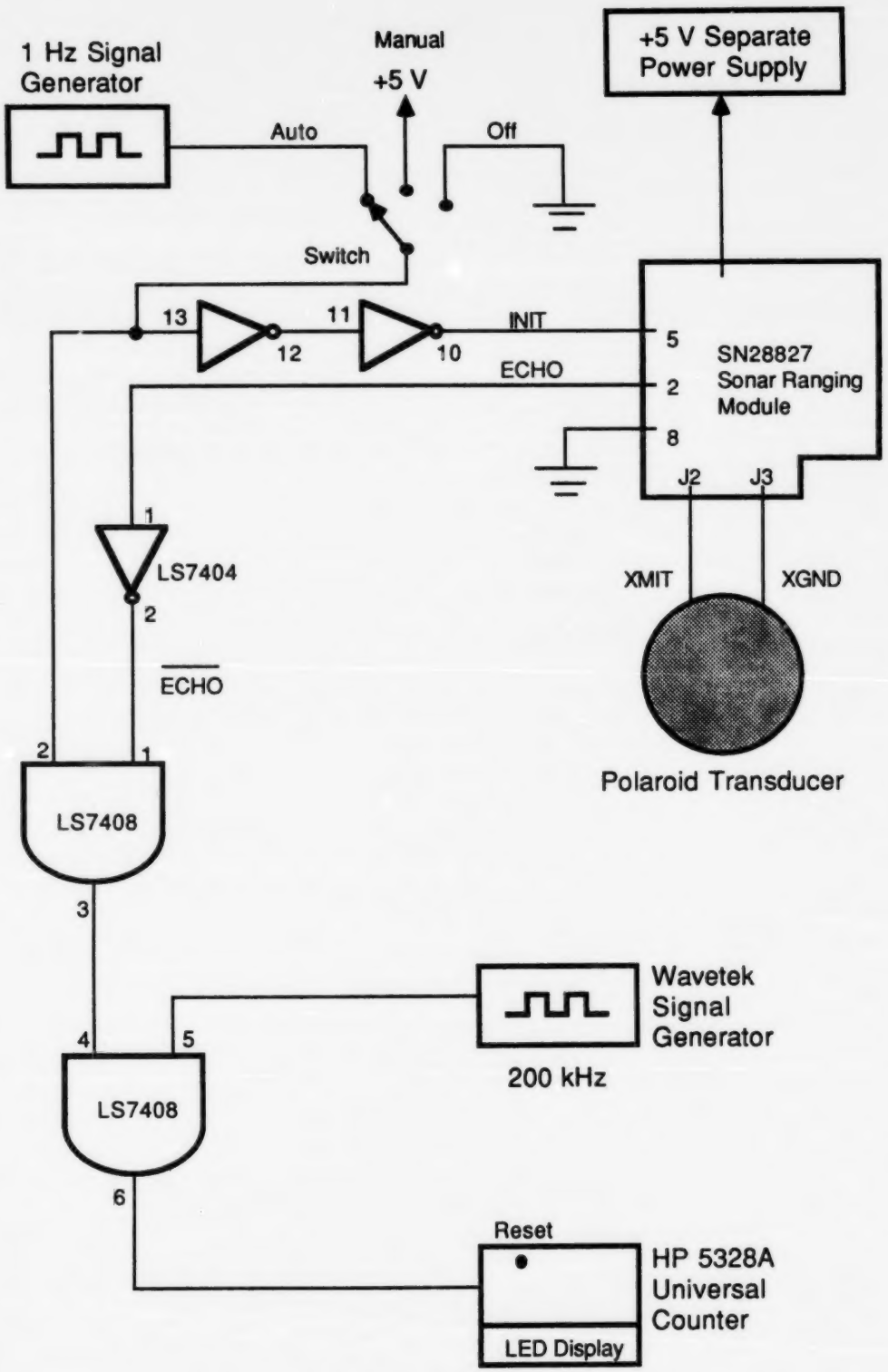


Figure A14/ Experimental Setup – Separate Power Supplies (March 24)

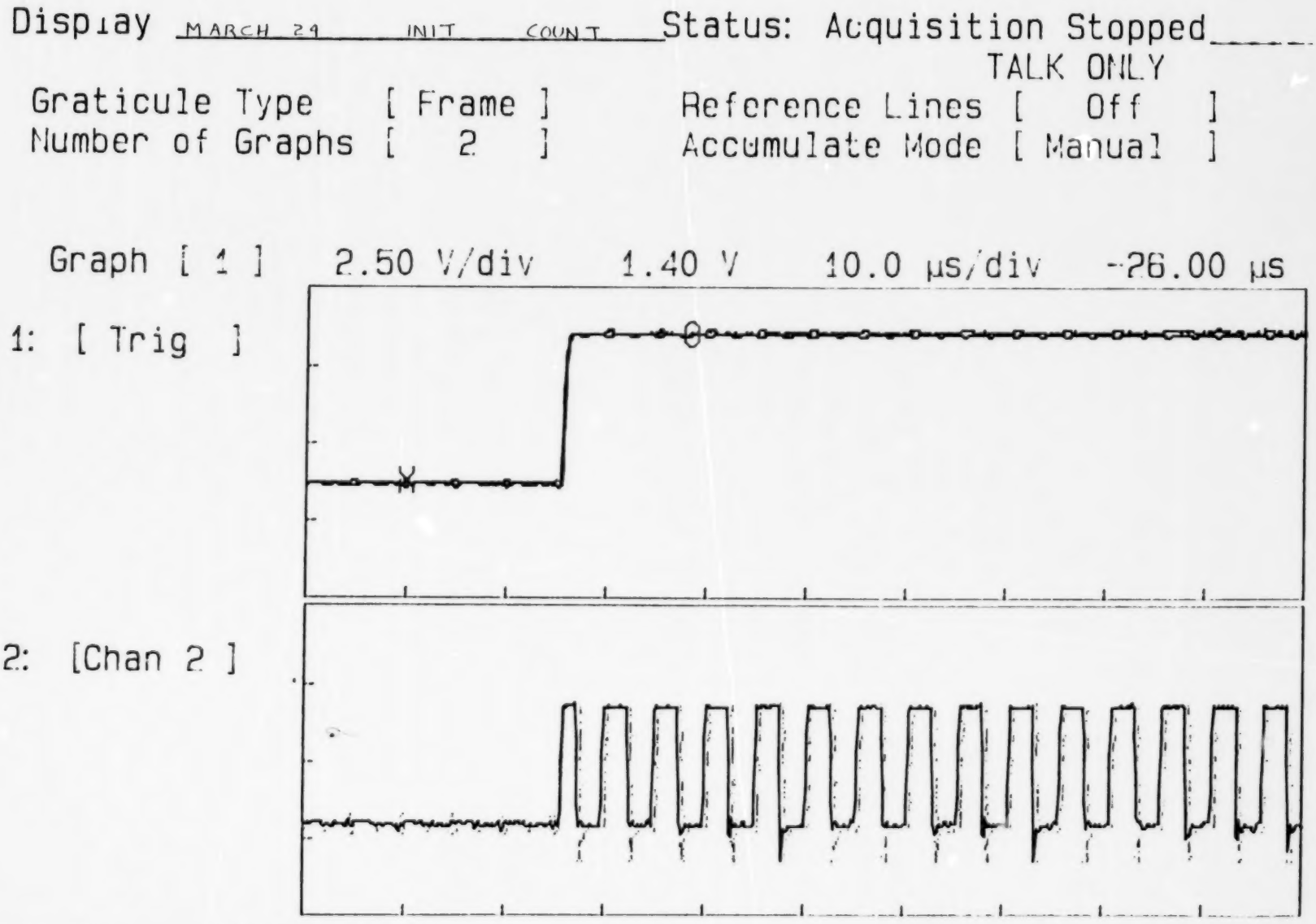

Display MARCH 24 INIT COUNT
Status: Acquisition Stopped
TALK ONLY
Graticule Type [Frame]
Number of Graphs [2]
Reference Lines [Off]
Accumulate Mode [Manual]
Graph [1] 2.50 V/div 1.40 V 10.0 µs/div -26.00 µs
1: [Trig]
2: [Chan 2]

Figure A15/ INIT and COUNT (March 24)

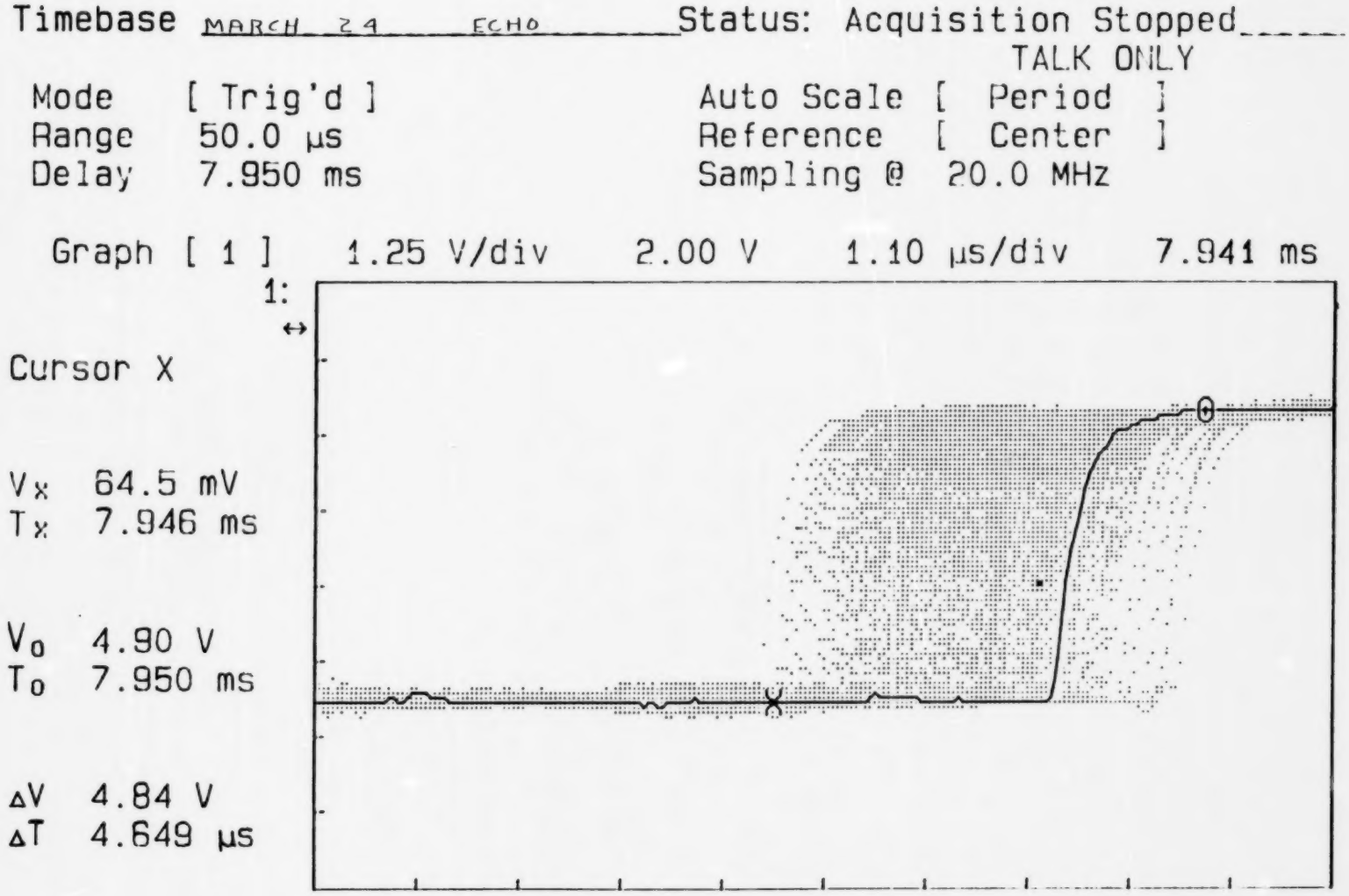


Figure A16/ ECHO (March 24)

SECTION 3
March 24 to March 26

FURTHER TESTS

With the measurements being more repeatable, further tests were done to characterize the unit. The test configuration was that of Figure A14.

TEST: 1.3 Changing the Clock Rate

DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: Varied
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall. The High Frequency Generator was set at 50 kHz and 10 readings were taken. Then, other frequencies were used up to 1 MHz. The frequency used, directly effects the counting rate. The higher the frequency, the more counts for the same distance reading, and the more accurate the conversion into millimeters.

MEASUREMENTS: A: 50 kHz C: 500 kHz
B: 200 kHz D: 1 MHz

	A	B	C	D	
	Count	Count	Count	Count	
1	423	1622	4124	8251	
2	423	1622	4123	8251	
3	423	1621	4124	8249	
4	423	1621	4124	8249	
5	423	1621	4123	8250	
6	423	1622	4124	8252	
7	423	1621	4124	8253	
8	423	1621	4124	8252	
9	423	1621	4123	8253	
10	423	1622	4124	8254	
Average Count	423	1621	4124	8251	
Average mm	1399	1459	1423	1423	
%	5.9	1.8	4.3	4.3	

TEST: 1.4 Repeatability

DATE: March 26/86
SENSOR HEIGHT: 974 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

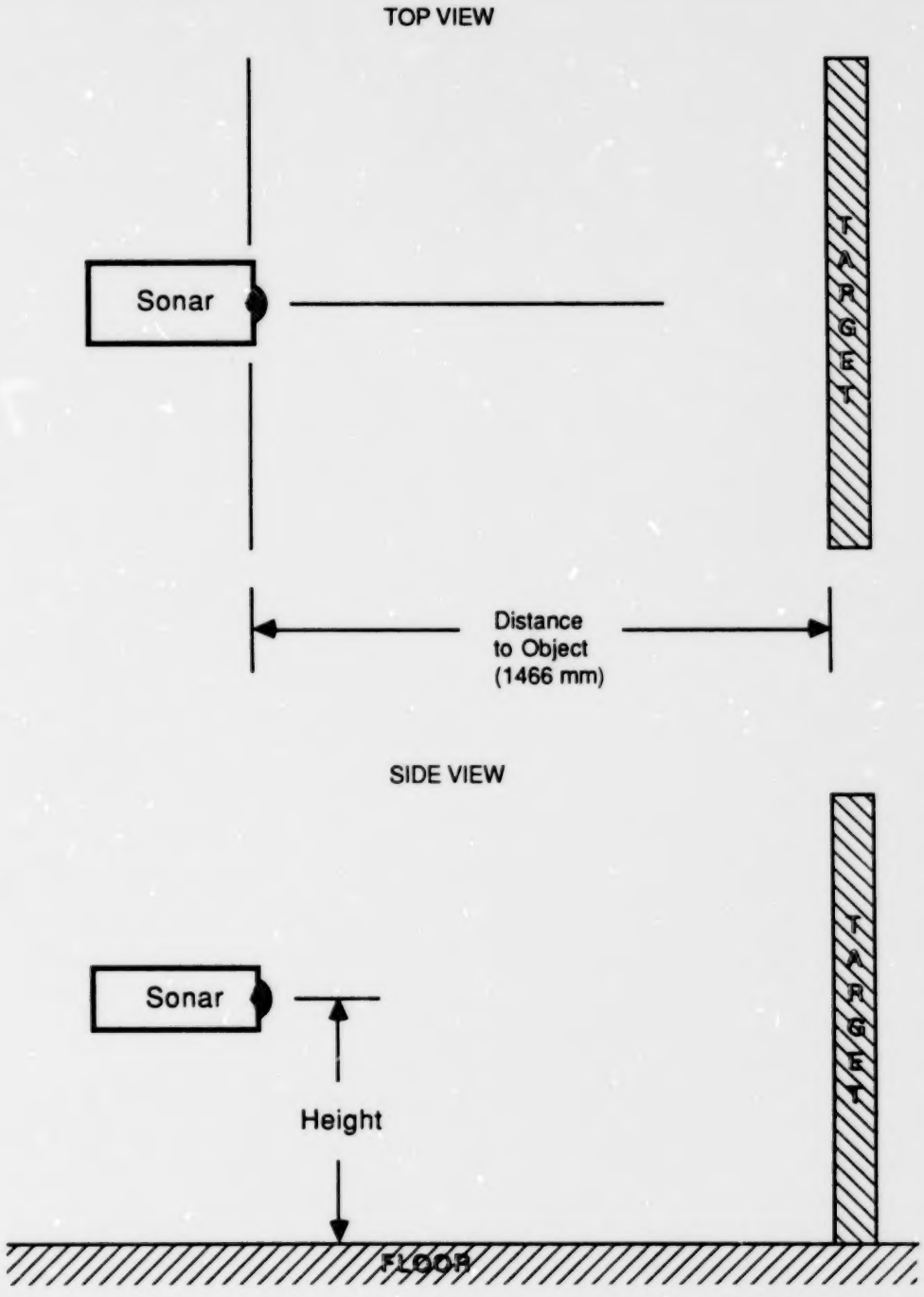
DESCRIPTION:

The sonar was positioned to face a flat plywood wall at a distance of 1466 mm. 25 measurements were taken. The aim of this experiment is to determine how close the readings are to each other when the test conditions are kept fixed.

MEASUREMENTS:

	Count	Count	
1	1590	1590	
2	1590	1590	
3	1590	1590	
4	1590	1590	
5	1590	1590	
6	1590		
7	1590		
8	1590		
9	1590		
10	1590		
11	1590		
12	1590		
13	1590		
14	1590		
15	1590		
16	1590		
17	1590		
18	1590		
19	1590		
20	1590		

Average Count = 1590
= 1371 mm % = 6.5



Test 1.4/ Repeatability

TEST:	2.1 Height

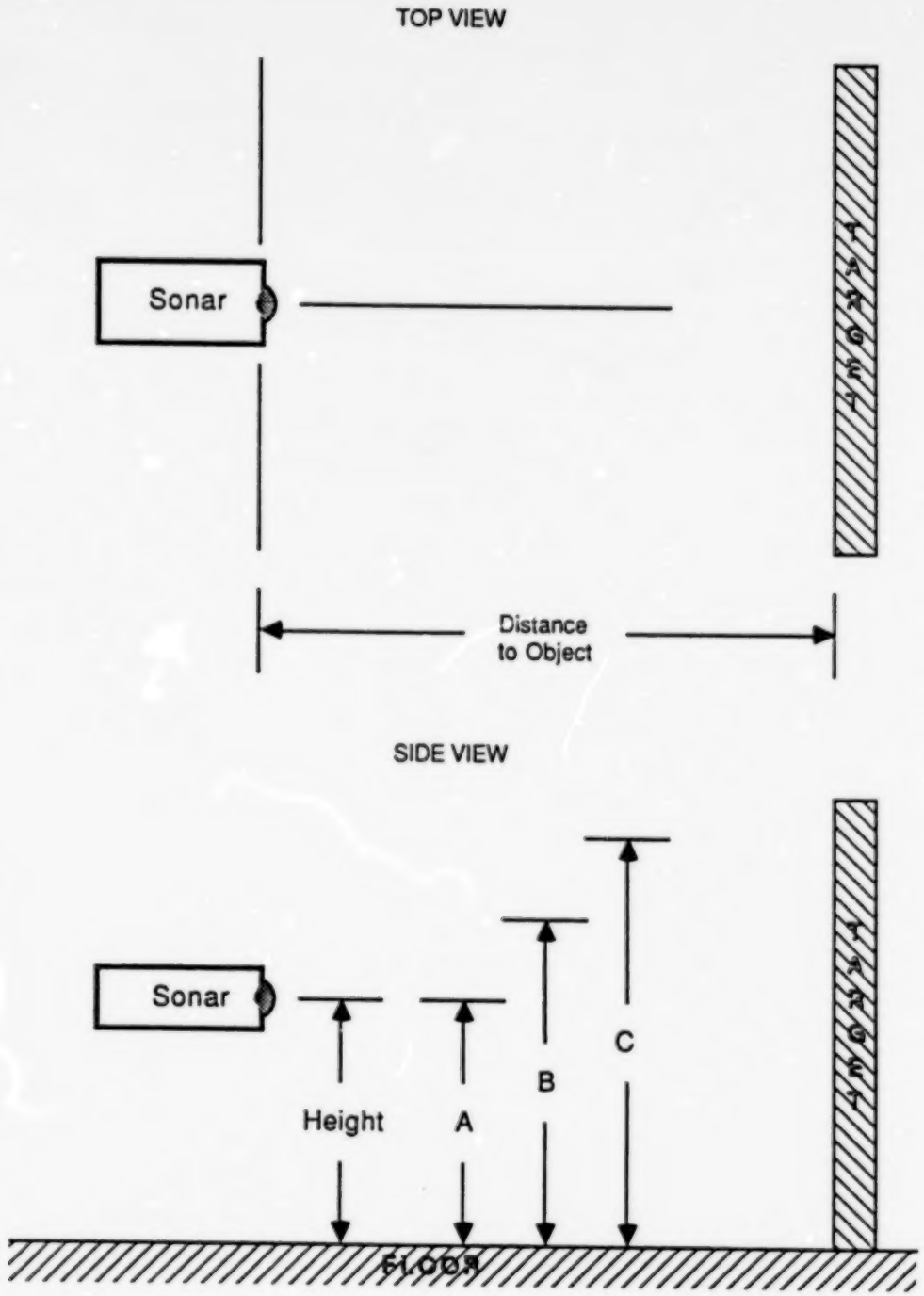
DATE: March 26/86
SENSOR HEIGHT: 60 mm - 615 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall in Position A. Readings were taken. Then the sonar was moved to position B at a different height. New readings were taken. Then C.

MEASUREMENTS:
A: Height = 60 mm
B: Height = 330 mm
C: Height = 615 mm

	A	B	C	
	Count	Count	Count	
1	1616	1619	1621	
2	1616	1619	1621	
3	1616	1619	1621	
4	1616	1616	1621	
5	1616	1619	1621	
6	1616	1619	1620	
7	1616	1619	1621	
8	1616	1616	1621	
9	1616	1619	1620	
10	1616	1616	1621	
Average Count	1616	1618	1620	
Average mm	1394	1396	1397	
%	6.2	6.1	6.1	



Test 2.1/ Height

TEST: 2.2 Angle to Reflected Surface

DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: AUTO

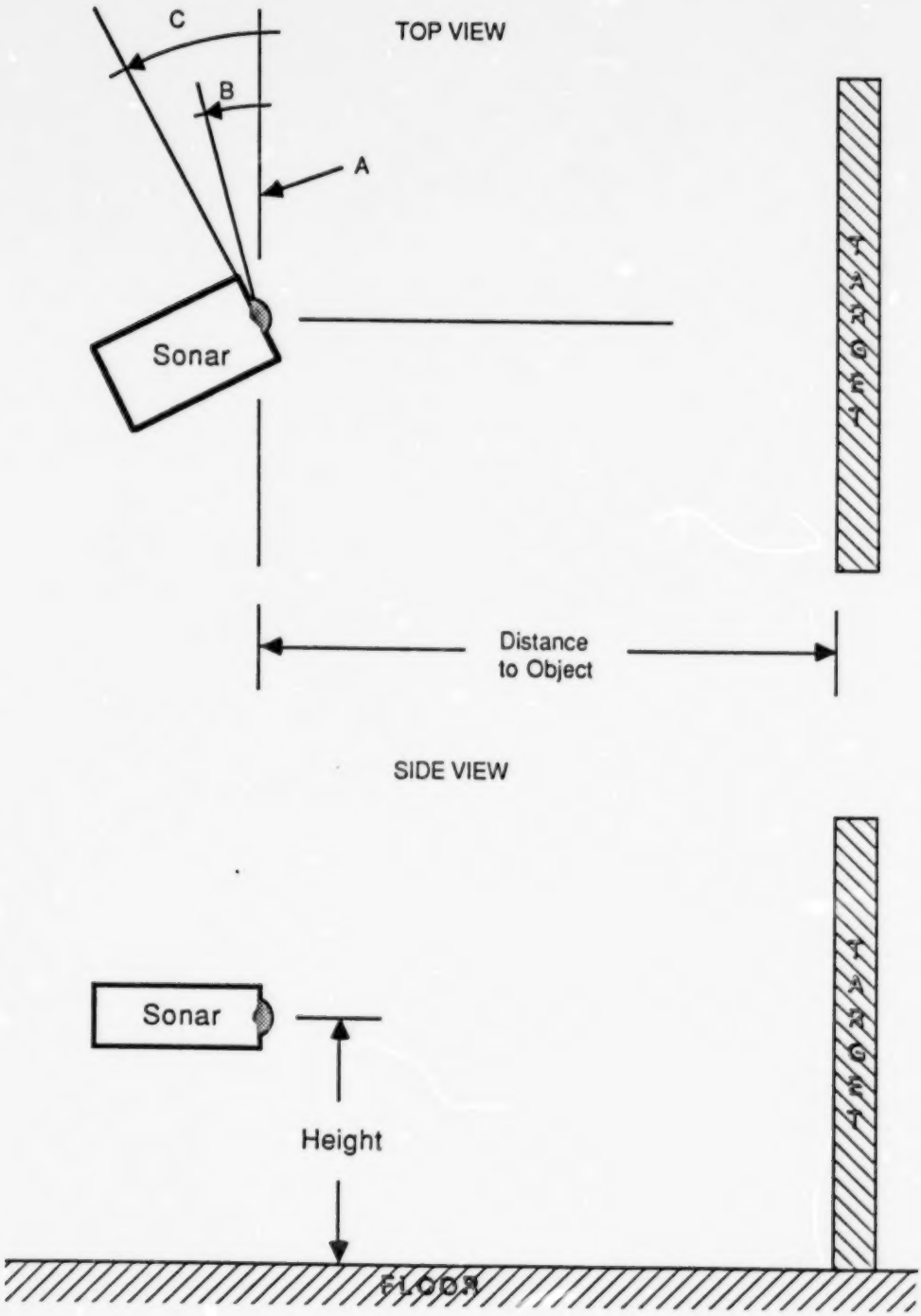
DESCRIPTION:

The sonar was positioned to face a flat plywood wall in position A. Readings were taken. Then the sonar was moved to position B at 5° to the wall. Ten readings were taken. Then it was placed at an angle of 7.4° to the wall at position C. Further readings were taken at position D (8.4°) and E (10°), also shown below.

MEASUREMENTS: Position A: 0°
Position B: 5°
Position C: 7.4°
Position D: 8.4°
Position E: 10°

Distance to target = 1048 mm

	A	B	C	D	E	
	Count	Count	Count	Count	Count	
1	1248	1256	1264	1278	----	
2	1248	1256	1264	1278	----	
3	1248	1256	1264	1281	----	
4	1248	1256	1264	1277	----	
5	1248	1256	1264	1278	----	
6	1248	1256	1264	----	----	
7	1248	1253	1267	1278	----	
8	1248	1256	1264	1286	----	
9	1248	1257	1264	1282	----	
10	1248	1256	1264	1273	----	
Average Count	1248	1256	1264	1279		
Average mm	1076	1083	1091	1103		
%	2.7	3.3	4.1	5.3		



Test 2.2/ Transducer Angle to Reflected Surface

TEST: 3.1 The Effect of Different Materials

DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall, Surface A. 10 readings were taken. Then, the material was changed to surface B and new readings taken, etc.

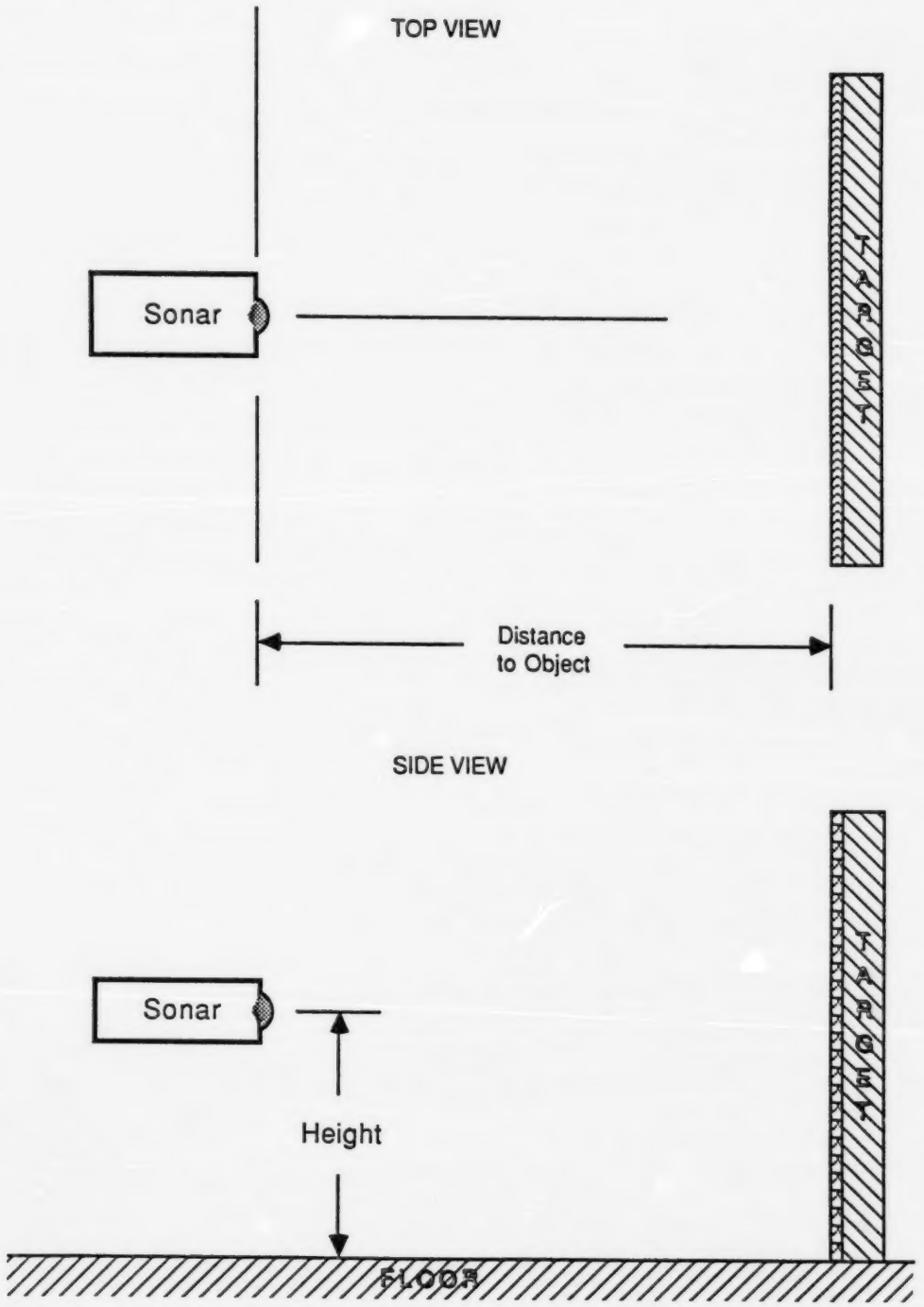
X = Distance to the target surface.

MEASUREMENTS:

Surface A:	Plywood	X = 1486 mm
Surface B:	Metal	X = 1484 mm
Surface C:	Glass	X = 1481 mm
Surface D:	Cardboard	X = 1478 mm
Surface E:	Foam	X = 1366 mm
Surface F:	Plastic	X = 1474 mm
Surface G:	Carpet	X = 901 mm

	A	B	C	D	F	G
	Count	Count	Count	Count	Count	Count
1	1617	1610	1607	1604	1606	943
2	1618	1610	1607	1603	1606	943
3	1618	1610	1607	1603	1606	943
4	1617	1610	1607	1603	1606	944
5	1618	1611	1608	1604	1606	944
6	1618	1611	1607	1603	1605	944
7	1617	1610	1607	1603	1606	944
8	1617	1610	1608	1603	1606	944
9	1618	1611	1608	1603	1605	944
10	1617	1611	1608	1603	1606	944
Average Count	1618	1610	1607	1603	1606	944
Average mm	1395	1389	1386	1383	1385	814
%	6.1	6.4	6.4	6.4	6.0	9.7

Note: There were no usable results for E as the surface was not reflective.



Test 3.1/ The Effect of Different Reflecting Materials

TEST: 3.2 The Effect of Different Objects - Pole

DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a metal pole in position A. 10 readings were taken. Then the sonar was moved to the left by X = 10 mm to position B. 10 readings were taken. Then the unit was moved further by another 10 mm to X = 20 mm to position C and so on.

MEASUREMENTS: Position A: X = 0 mm, D: X = 50 mm
Position B: X = 10 mm, E: X = 75 mm
Position C: X = 20 mm, F: X = 80 mm

Distance to pole when X = 0 is 668 mm

	A	B	C	D	E	F
	Count	Count	Count	Count	Count	Count
1	734	734	735	741	756	1617
2	734	735	735	741	757	1617
3	734	735	735	741	757	1617
4	734	735	735	741	757	1617
5	734	734	735	742	757	1617
6	734	735	735	741	756	1617
7	734	735	735	741	756	1617
8	734	734	735	741	756	1617
9	734	735	735	741	756	1617
10	734	735	735	741	756	1617
Average Count	734	735	735	741	756	1617
Average mm	633	634	634	639	652	1395
%						

TEST: 3.2 The Effect of Different Objects - Pole (Cont'd)

DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

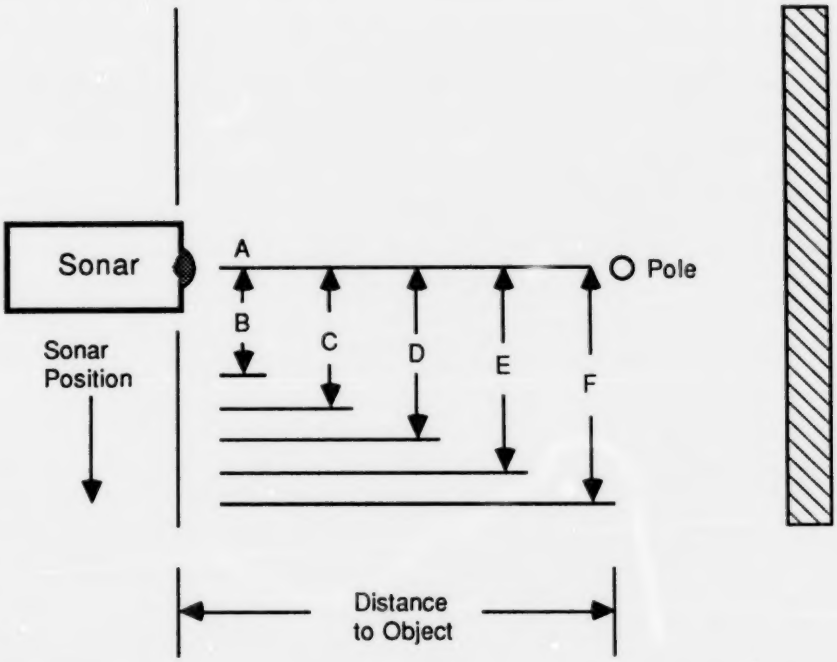
The sonar was positioned to face a metal pole in position A. 10 readings were taken. Then the sonar was moved to the left by X = 10 mm to position B. 10 readings were taken. Then the unit was moved further by another 10 mm to X = 20 mm to position C and so on.

MEASUREMENTS: Position A: X = 0 mm, D: X = 50 mm
Position B: X = 10 mm, E: X = 70 mm
Position C: X = 20 mm, F: X = 75 mm

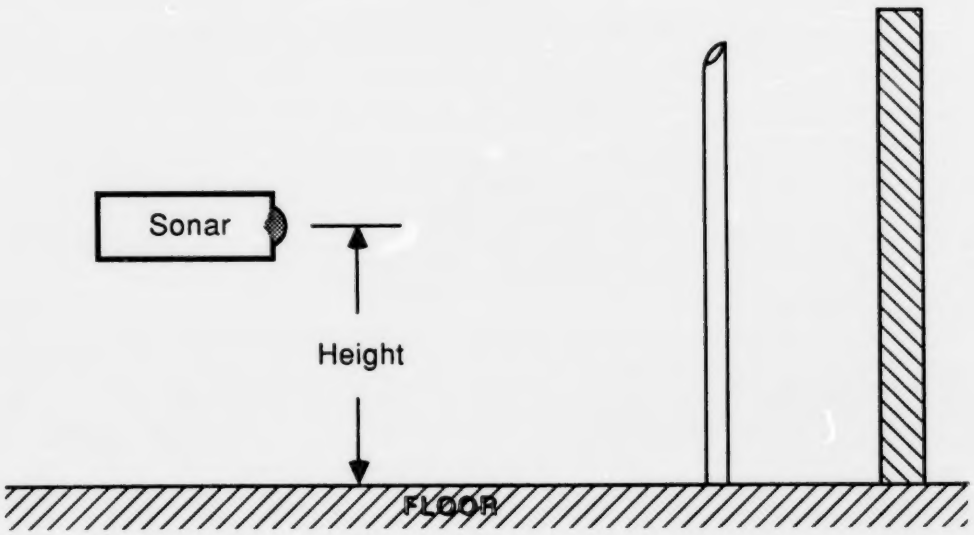
Distance to pole when X = 0 is 494 mm

	A	B	C	D	E	F
	Count	Count	Count	Count	Count	Count
1	571	572	572	579	597	1617
2	571	572	573	579	601	1617
3	571	571	573	579	601	1617
4	571	572	573	579	601	1616
5	572	572	572	579	601	1617
6	572	572	573	579	598	1617
7	571	572	573	579	598	1617
8	571	572	573	579	598	1617
9		572	573	579	601	1617
10					598	1617
Average Count	571	571	573	579	599	1617
Average mm	493	493	494	499	516	1395
%						

TOP VIEW



SIDE VIEW



Test 3.2/ Reflection from Different Objects - Pole

TEST:	4.2 Acoustical Horns

DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall. An Acoustical Horn of length L was placed on the transducer. A metal target was placed 668 mm away and in the beams center. 10 readings were taken. Then the target was moved X = 10 mm away from the center of the beam and 10 more readings were taken. This was repeated until the target could no longer be detected. With this information, the beam width BW can be determined. This process was repeated with different horn lengths. The aim of this experiment was to determine how the beam width BW varies with a horns length L.

MEASUREMENTS: Distance to Target at X = 0 is 668 mm

@ = ARCTAN X/668

Beam Width = 2 x @ evaluated when X is the length from the center of the beam to the outer edge.

	Horn Length L = 0 mm					
(mm) (deg.)	X=0 @=0	X=10 @=0.9	X=20 @=1.7	X=30 @=2.6	X=40 @=3.4	X=50 @=4.3
	Count	Count	Count	Count	Count	Count
1	732	732	732	733	734	735
2	732	732	732	733	734	735
3	732	732	733	733	734	736
4	732	732	733	734	734	736
5	732	732	733	734	734	736
6	732	732	732	733	735	736
7	732	732	733	733	734	736
8	732	732	733	733	734	736
9	732	732	733	733	734	736
10	732	732	733	734	734	736
Average Count	732	732	733	733	734	736
Average mm	632	632	633	633	633	634

	X=60 @=5.1	X=70 @=6.0	X=80 @=6.8	X=90 @=7.7	X=100 @=8.5	X=101 @=8.5
	Count	Count	Count	Count	Count	Count
1	737	741	742	751	774	1615
2	740	741	742	751	774	1615
3	737	741	742	751	774	1615
4	737	741	743	748	778	1615
5	737	741	743	751	769	1615
6	737	741	742	752	766	1615
7	737	741	742	751	765	1615
8	740	741	742	751	781	1615
9	737	741	743	752	765	1615
10	740	741	743	751	766	1615
Average Count	737	741	742	750	771	1615
Average mm	636	639	640	648	664	1393

Calculated BW = 2 x 8.5
= 17 degrees

	Horn Length L = 45 mm					
(mm) (deg.)	X=0 @=0	X=10 @=0.9	X=20 @=1.7	X=30 @=2.6	X=40 @=3.4	X=50 @=4.3
	Count	Count	Count	Count	Count	Count
1	731	731	732	732	734	738
2	731	731	732	733	734	739
3	731	731	732	733	734	738
4	731	731	732	733	734	739
5	731	731	732	733	734	738
6	731	731	732	733	734	739
7	731	731	732	733	734	738
8	731	731	732	733	734	738
9	731	731	732	733	734	739
10	731	731	732	733	734	739
Average Count	731	731	732	733	734	739
Average mm	631	631	631	632	633	637

	X=60 @=5.1	X=70 @=6.0	X=80 @=6.8	X=90 @=7.7	X=92 @=7.8	X=101 @=8.5
	Count	Count	Count	Count	Count	Count
1	740	744	750	761	777	1614
2	741	745	747	751	785	1614
3	741	745	751	751	765	1614
4	741	745	751	768	769	1614
5	740	745	751	761	1614	1614
6	740	745	747	752	1614	1614
7	740	744	747	761	793	1615
8	740	745	750	761	765	1614
9	740	745	747	762	773	1615
10	741	745	750	761	777	1614
Average Count	740	745	749	759	–	1614
Average mm	638	642	646	655	–	1393

Calculated BW ≅ 2 x 7.8
= 15.6 degrees

	Horn Length L = 90 mm					
(mm) (deg.)	X=0 @=0	X=10 @=0.9	X=20 @=1.7	X=30 @=2.6	X=40 @=3.4	X=50 @=4.3
	Count	Count	Count	Count	Count	Count
1	731	731	732	732	734	739
2	731	731	732	733	734	739
3	731	731	732	732	734	739
4	731	731	732	733	735	739
5	731	731	732	733	735	739
6	731	731	732	732	735	739
7	731	731	732	733	735	739
8	731	731	732	732	735	739
9	731	731	732	732	735	739
10	731	731	732	732	735	739
Average Count	731	731	732	732	735	739
Average mm	631	631	632	632	634	637

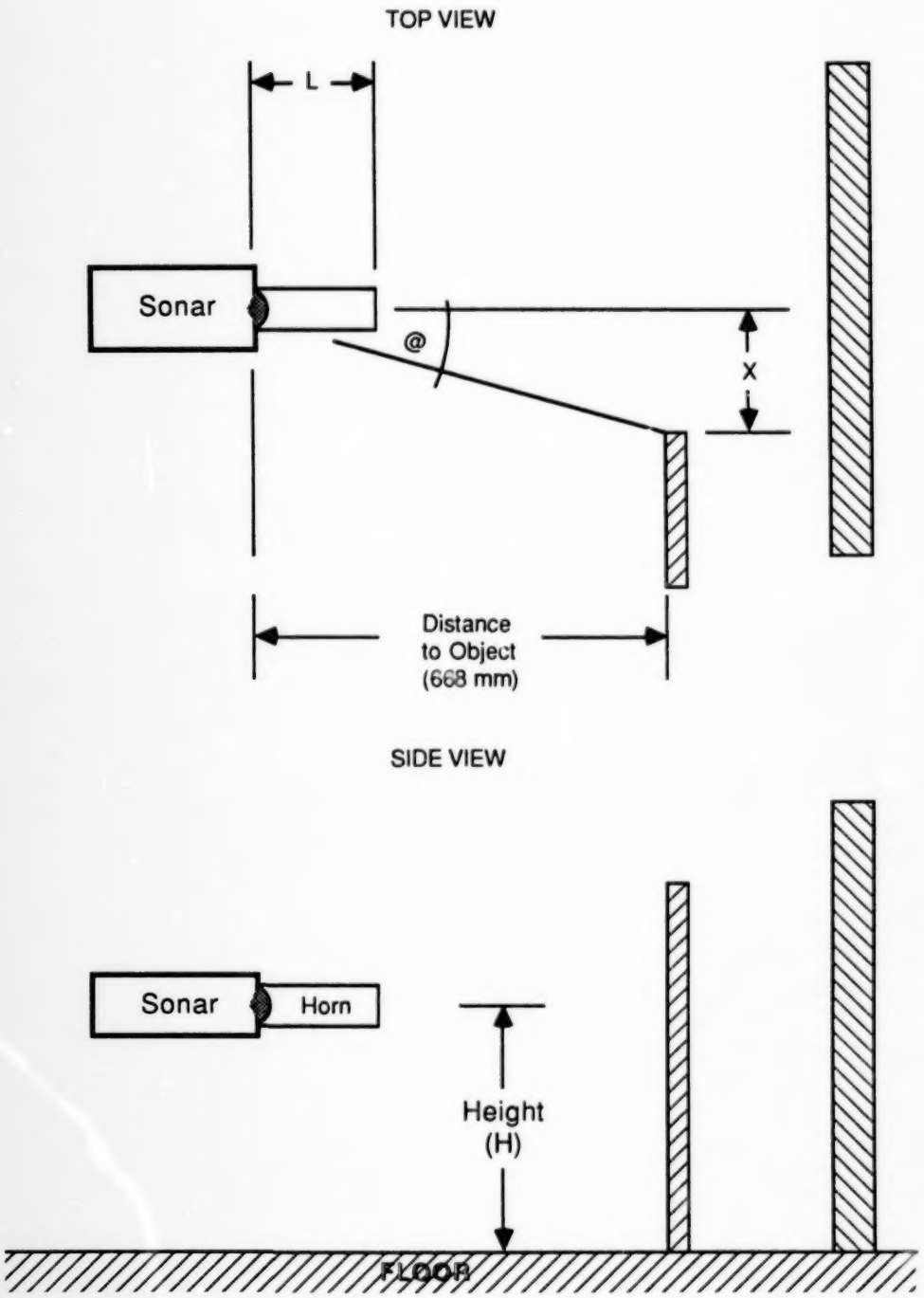
	X=60 @=5.1	X=70 @=6.0	X=80 @=6.8	X=84 @=7.2	X=85 @=7.3	X=86 @=7.3
	Count	Count	Count	Count	Count	Count
1	741	746	767	776	789	1615
2	741	750	764	772	1616	1615
3	741	750	767	776	1616	1615
4	741	750	764	775	789	1615
5	741	750	764	776	1616	1615
6	742	750	764	776	784	1615
7	742	750	763	776	784	1615
8	742	750	764	772	780	1615
9	742	750	767	776	1615	1615
10	741	750	767	776	780	1615
Average Count	741	750	765	775	–	1615
Average mm	639	647	660	668	–	1393

Calculated BW $\cong$ 2 x 7.3
= 14.6 degrees

	Horn Length L = 134 mm					
(mm) (deg.)	X=0 @=0	X=10 @=0.9	X=20 @=1.7	X=30 @=2.6	X=40 @=3.4	X=50 @=4.3
	Count	Count	Count	Count	Count	Count
1	731	731	732	733	737	739
2	730	732	733	733	738	740
3	730	731	732	733	738	740
4	731	732	732	733	737	740
5	731	731	732	733	738	740
6	730	731	732	733	738	740
7	731	731	732	733	737	740
8	731	731	732	733	738	740
9	731	731	732	733	737	740
10	731	731	732	733	738	740
Average Count	731	731	732	733	738	740
Average mm	631	631	632	632	637	638

	X=52 @=4.5	X=55 @=4.7	X=57 @=4.9	X=58 @=5.0	X=59 @=5.1	X=60 @=5.1
	Count	Count	Count	Count	Count	Count
1	743	747	756	769	781	1614
2	744	748	753	765	785	1614
3	744	748	757	773	786	1614
4	744	748	753	773	781	1614
5	743	748	756	765	782	1614
6	743	748	756	769	781	1614
7	743	748	756	765	779	1615
8	743	748	757	769	778	1615
9	744	748	753	761	778	1615
10	743	748	756	765	782	1614
Average Count	743	748	755	767	781	1614
Average mm	641	645	651	662	674	1393

Calculated BW $\cong$ 2 x 5.1
= 10.2 degrees



Test 4.2/ Acoustical Horns

TEST: 5.1 Interference from 2 Units

DATE: March 26/86
SENSOR HEIGHT: 974 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

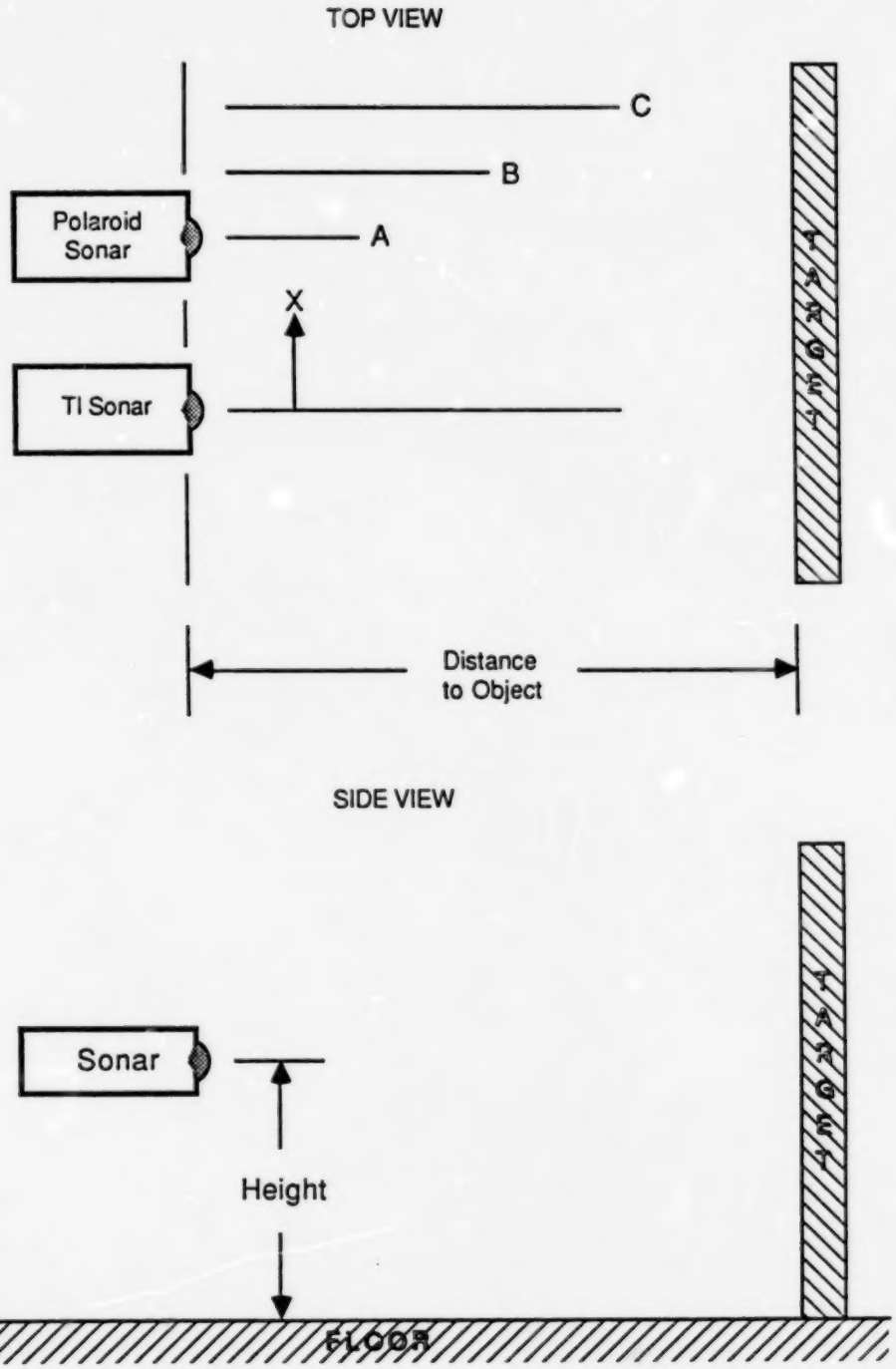
DESCRIPTION:

The sonar was positioned to face a flat plywood wall. A second sonar unit (Polaroid) was placed in position A, a set distance beside the first. Readings were taken initially with the second unit off, then with the second unit on. Then this was repeated with a different spacing X.

MEASUREMENTS: Position A: X = 200 mm
Position B: X = 400 mm
Position C: X = 600 mm

Distance to target = 1466 mm

	A		B		C	
Unit 2	OFF	ON	OFF	ON	OFF	ON
	Count	Count	Count	Count	Count	Count
1	1590	1000	1590	1590	1590	1590
2	1590	909	1590	1590	1590	612
3	1590	1590	1590	1590	1590	1529
4	1590	1424	1590	1590	1590	1123
5	1590	1590	1590	1590	1590	726
6	1590	649	1590	1590	1590	1590
7	1590	1590	1590	1590	1590	1590
8	1590	924	1590	1495	1590	1590
9	1590	1464	1590	1590	1590	1588
10	1590	495	1590	490	1590	1590
Average Count	1590		1590		1590	
Average mm	1371		1371		1371	



Test 5.1/ Interference Between 2 Units

TEST: 5.2 Interference from a Vacuum

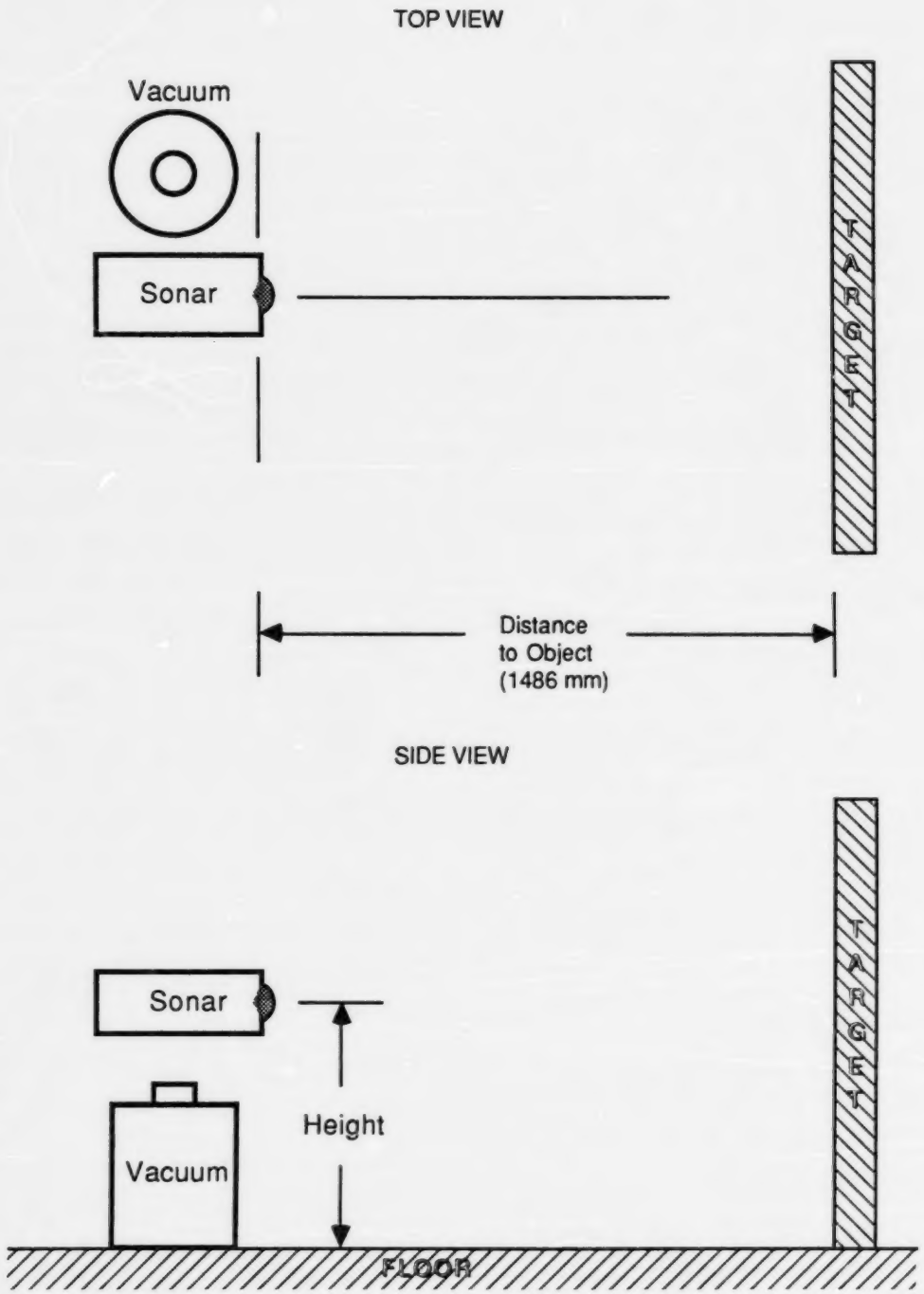
DATE: March 26/86
SENSOR HEIGHT: 330 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall at a distance of 1486 mm. An industrial Wet - Dry Vacuum cleaner was placed beside the unit. 30 measurements were taken with the vacuum off and then 30 were taken with it on. The aim of this experiment was to see if an industrial vacuum operating in the vicinity of the sonar would interfere in its operation.

MEASUREMENTS:

	Vacuum Off		Vacuum On		
	Count	Count	Count	Count	
1	1617	1617	1617	1617	
2	1617	1617	1617	1617	
3	1617	1617	1617	1617	
4	1618	1617	1617	1617	
5	1617	1618	1617	1617	
6	1618	1617	1617	1617	
7	1618	1617	1617	1617	
8	1617	1617	1618	1617	
9	1617	1617	1617	1617	
10	1618	1617	1617	1617	
11	1618	1617	1617	1617	
12	1617	1617	1617	1617	
13	1618	1617	1617	1617	
14	1617	1617	1617	1617	
15	1617	1617	1617	1617	



Test 5.2/ Interference from a Vacuum

TEST: 5.3 Interference from Vibration

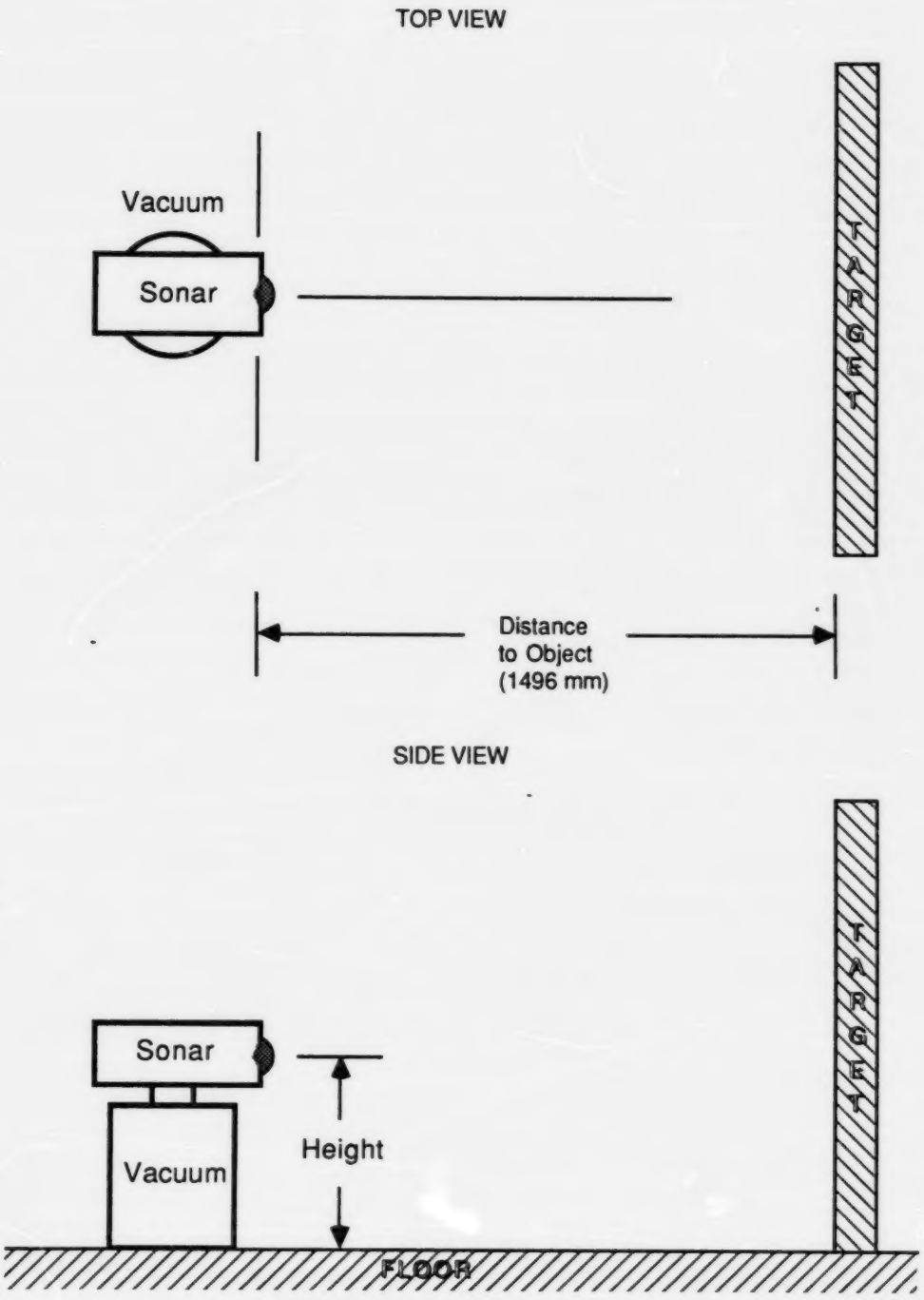
DATE: March 26/86
SENSOR HEIGHT: 800 mm
COUNTER FREQUENCY: 200 kHz
SAMPLE RATE: Auto

DESCRIPTION:

The sonar was positioned to face a flat plywood wall at a distance of 1496 mm. The sonar was placed on top of an industrial Wet - Dry Vacuum Cleaner so that the vibrations passed into the sonar. 30 measurements were taken with the vacuum off and then 30 were taken with it on. The aim of this experiment was to see if vibrations from the Vacuum would interfere with the operation of the sonar unit.

MEASUREMENTS:

	Vacuum Off		Vacuum On		
	Count	Count	Count	Count	
1	1629	1629	1630	1629	
2	1629	1629	1629	1629	
3	1629	1629	1629	1629	
4	1629	1629	1629	1629	
5	1630	1629	1629	1630	
6	1629	1629	1629	1629	
7	1629	1629	1629	1630	
8	1629	1629	1629	1629	
9	1629	1629	1629	1629	
10	1629	1629	1629	1629	
11	1629	1629	1629	1629	
12	1629	1629	1629	1629	
13	1629	1629	1629	1629	
14	1629	1629	1629	1629	
15	1629	1629	1630	1629	



Test 5.3/ Interference from Vibration

Part II/ H5 Subway Car Test

GENERAL

The tests from this section were conducted in an H5 subway car at the Davisville yard, April 8/86.

The equipment used was identical to that used in the lab test section with the exception that the logic gates were now on a small PC board instead of a breadboard. The small PC board was installed into the box housing the sonar unit.

The aim of this experiment was to look for any interference caused in the subway car that would effect the sonar. As well, accuracy, repeatability, and object detection were tested.

RESULTS (Refer to Figure A17)

The doors of the subway car were vibrating and caused readings in this region to vary by up to 25 counts between samples (Area X).

Curved sections under each seat (Area Y) could not be measured.

Equipment under the floor would occasionally come on and off but did not appear to interfere with readings.

The equipment was operated in all sections of the car with no noticeable interference (excluding mentioned areas).

Figure A18 shows an approximation of the readings obtained by moving a sensor from position A1 to A2 on Figure A17. Beginning at A1 facing the door, the readings could vary by up to 25 counts, depending on how the door was vibrating. As the divider came into the units range, the readings began to decrease in value, but a large variation between samples still existed. Eventually, the range finder's measurements reached a minimum, indicating it had found the front of the divider, and became consistent. Then, the readings became slightly larger and not as consistent again, while the metal base came into range. Once the sonar came into range of the curved section, no distinguishable readings could be maintained. Then, the flat base grill came into view, and good, consistent readings could be produced.

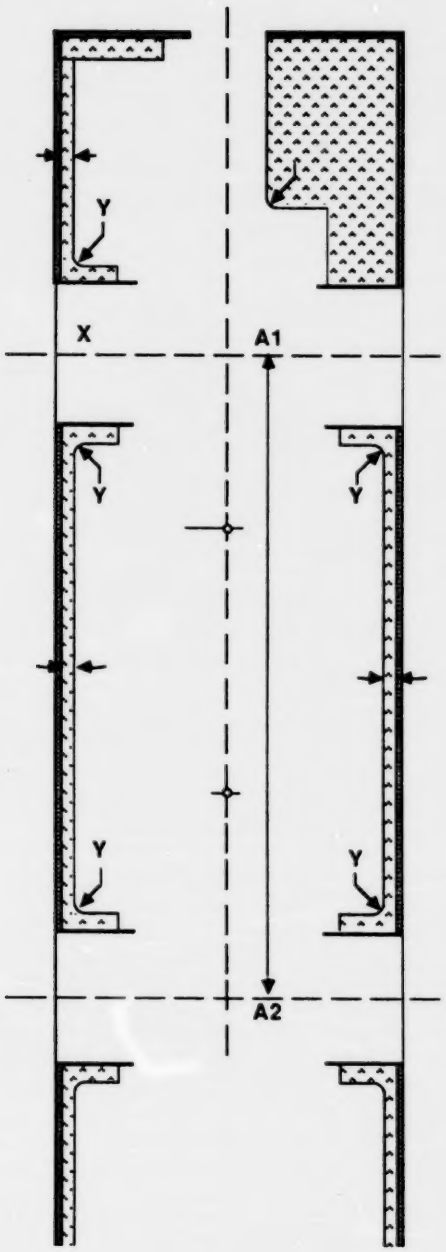


Figure A17/ H5 Subway Car Section

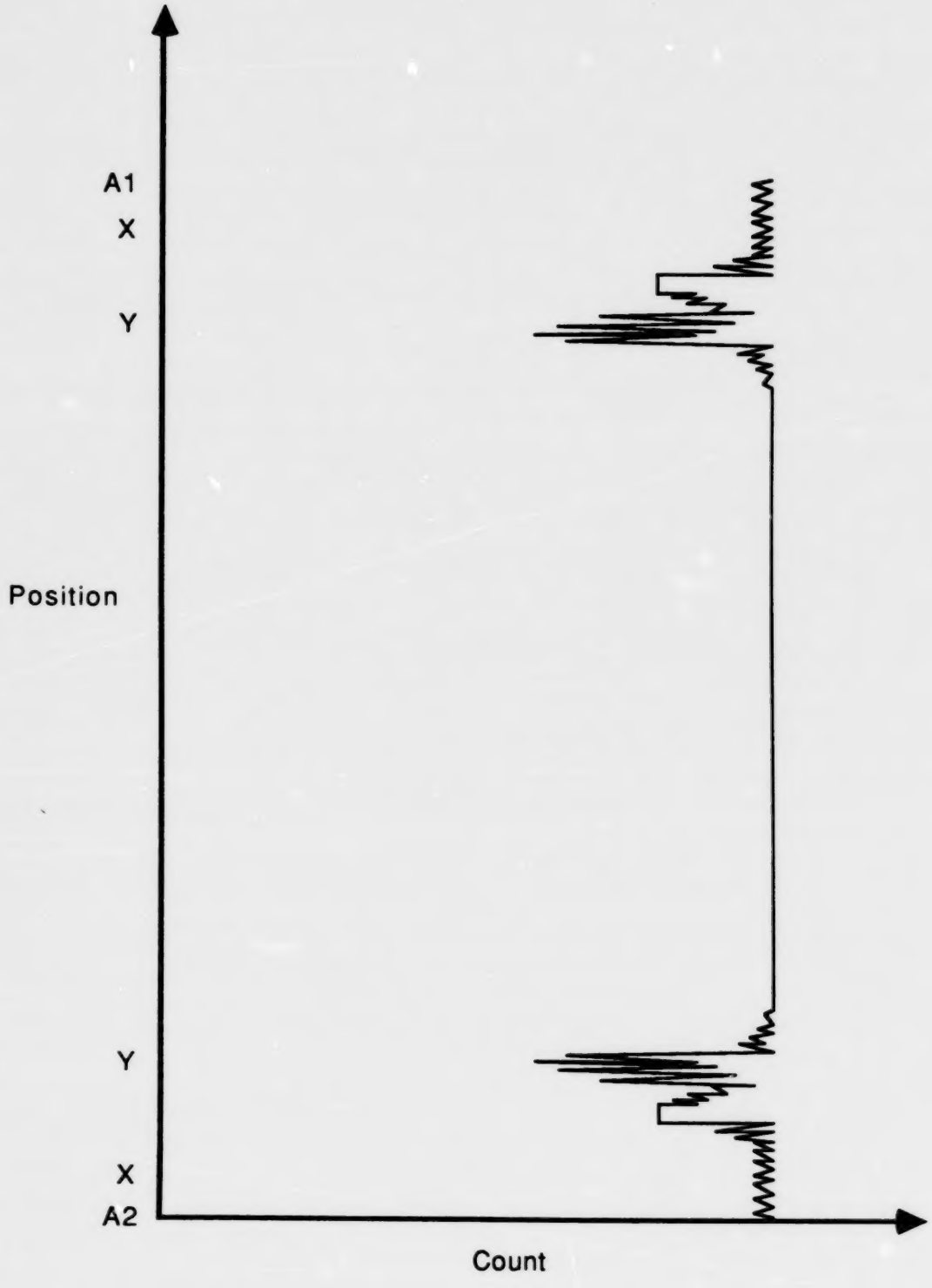


Figure A18/ Example of Sonar Readings in H5 Subway Car

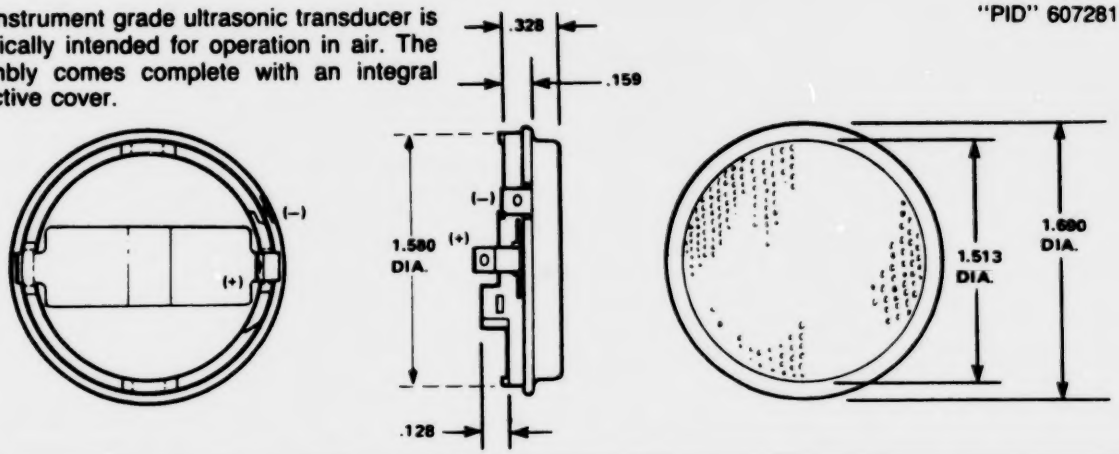
APPENDIX B/ POLAROID TRANSDUCER

ENVIRONMENTAL ULTRASONIC TRANSDUCER

Polaroid

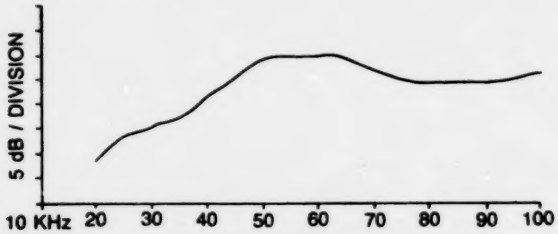
"PID" 607281

This instrument grade ultrasonic transducer is specifically intended for operation in air. The assembly comes complete with an integral protective cover.



ELECTRO-ACOUSTIC CHARACTERISTICS

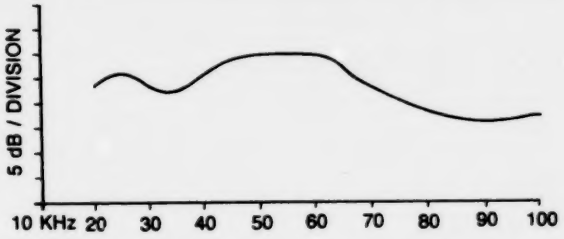
Type	Electrostatic
Usable Transmitting Frequency Range	See Graph 1
Usable Receiving Frequency Range	See Graph 2
Beam Pattern	See Graph 3
Minimum Transmitting Sensitivity at 50kHz 300 VAC pk-pk, 150 VDC bias (dB re 20 uPa at 1 meter)	110dB
Minimum Receiving Sensitivity at 50 kHz 150 VDC bias (dB re 1v/Pa)	–42 dB
Suggested DC Bias Voltage	150V
Suggested AC Driving Voltage (peak)	150V
Maximum Combined Voltage	400V
Capacitance at 1 kHz (typical) 150 VDC bias	400pf



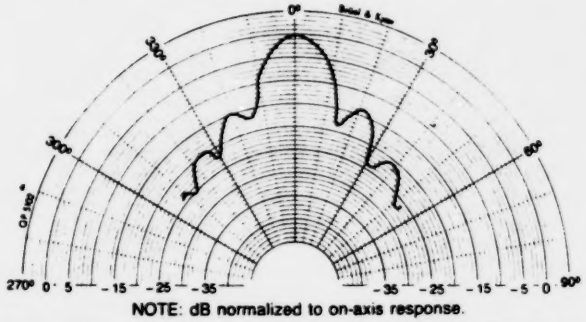
GRAPH 1. TYPICAL TRANSMIT RESPONSE

MECHANICAL CHARACTERISTICS

Construction	
Diaphragm	24K gold on Kapton Film
Housing	Stainless Steel



GRAPH 2. TYPICAL FREE FIELD RECEIVE RESPONSE



NOTE: dB normalized to on-axis response.

GRAPH 3. TYPICAL BEAM PATTERN AT 50 KHz

ENVIRONMENTAL CHARACTERISTICS — OPERATIONAL

Temperature Range	–20°F to 160°F (–30°C to 70°C)

Combined transmit and receive sensitivity variation is less then 6 dB over this range.

Relative Humidity	5% to 95% non-condensing

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ENVIRONMENTAL CHARACTERISTICS — EXPOSURE

NOTE: The following tests were performed with the transducer housed in the ***POLAROID TEST ENCLOSURE (see FIGURE 1).*** *The* ***TEST ENCLOSURE*** *protects the sides and back of the transducer from exposure to any foreign matter. The rear of the transducer is vented to atmospheric pressure. Output and sensitivity of the transducer are reduced slightly when used in this enclosure.*

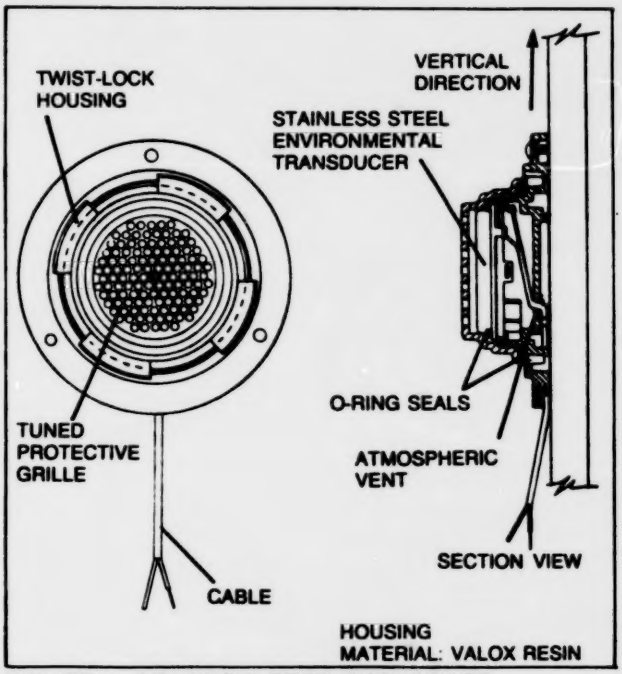


FIGURE 1. POLAROID TEST ENCLOSURE

After each test, transducers were cleaned and dried if necessary. Measurements were then taken at room temperature.

Variation in combined transmit/receive sensitivity at 50kHz was no more than 4.5 dB after any one of the following tests.

Storage Temperature Range — –40°F to 250°F (–40°C to 120°C)

Salt Spray Exposure
5% salt spray solution at 95°F (35°C) — 96 hours

Shock and Vibration
50 G peak in each direction along 3 perpendicular axes, pulse duration: 6.5 ms;
6 G's RMS 20 - 2000 Hz for 6 minutes

Water Immersion (vent hole sealed) — 24 hours

Freeze/Thaw Cycle — 4 cycles
Spray with water, drain, expose to –20°F (–30°C) for 20 minutes, allow to warm to room temperature.

Chemical Exposure
Gasoline, acetone, sulphur dioxide. Samples sprayed with/exposed to chemical then placed in 120°F (49°C)/90% relative humidity environment for 24 hours.

Sand Bombardment — 20 cycles
50ml fine sand poured from 4 feet onto front grill

No claim for performance is made without an enclosure providing protection equal to or better than that provided by the **POLAROID TEST ENCLOSURE.** Similarly, no claim is made for performance in any other environments or under any other conditions than those described herein.

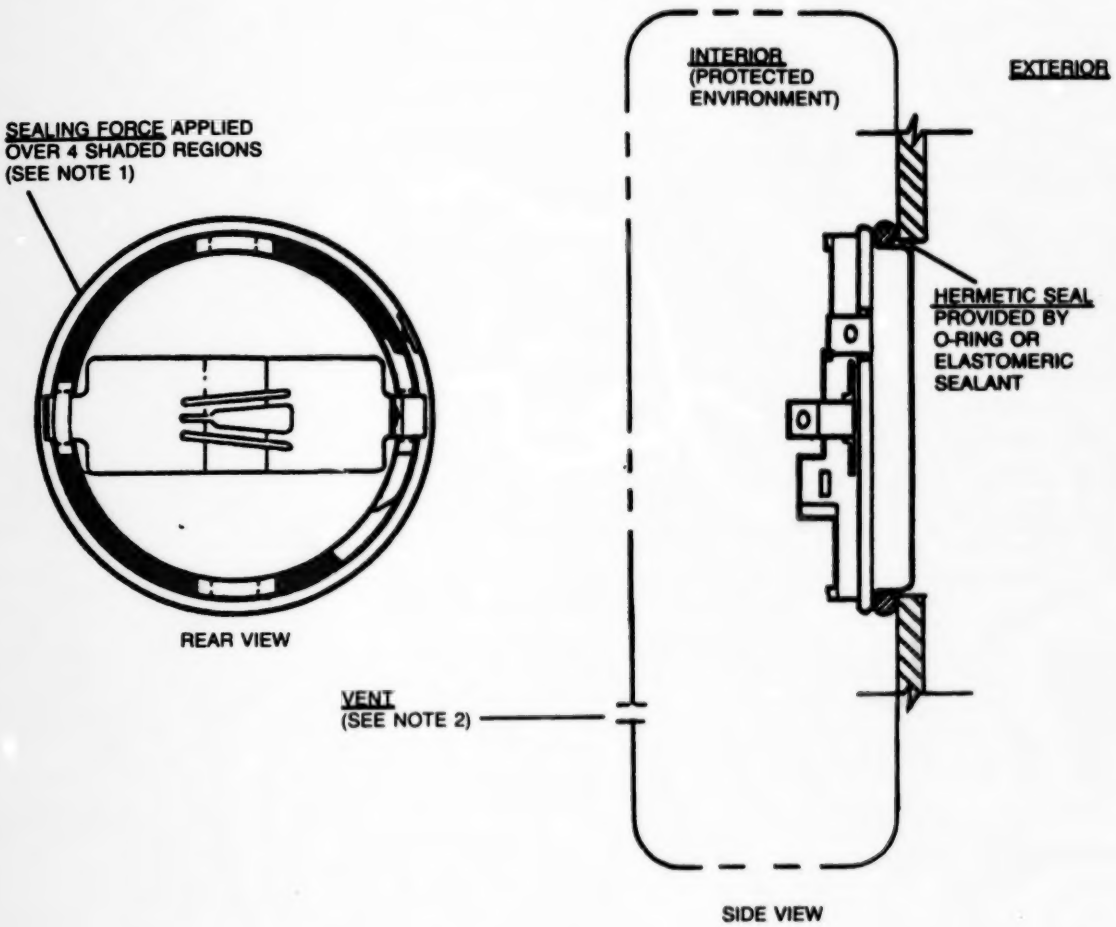
SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE.

WARRANTY: We will, within 90 days from date of shipment, replace or, at our option, repair any products or parts thereof sold hereunder which are found to be defective in material or workmanship. Our obligation with respect to such products or parts shall be limited to replacement or repair f.o.b. Cambridge, Mass. and in no event shall we be liable for consequential or special damages, or for transportation, installation, adjustment, or other expenses which may arise in connection with such products or parts. No waiver, alteration or modification of this paragraph shall be valid unless made in writing and signed by an executive officer of Polaroid.

For technical assistance call Polaroid's Applications Engineers at 617-577-4681.

ENVIRONMENTAL ULTRASONIC TRANSDUCER MOUNTING SUGGESTIONS

The following guidelines should be used when designing your own housing for the Polaroid Environmental Ultrasonic Transducer.


SEALING FORCE APPLIED OVER 4 SHADED REGIONS (SEE NOTE 1)
REAR VIEW
INTERIOR (PROTECTED ENVIRONMENT)
EXTERIOR
HERMETIC SEAL PROVIDED BY O-RING OR ELASTOMERIC SEALANT
VENT (SEE NOTE 2)
SIDE VIEW

NOTE 1

A uniform force must be applied on the plastic ring shown if an O-ring is used as a seal. The use of an elastomeric sealant such as RTV silicone rubber eliminates the need for a seal clamping mechanism.

NOTE 2

Provisions must be made to provide for equalization of air pressure between the front and rear of the transducer. The location and design of this vent must be such that water, dust, corrosives, or foreign matter are prevented from reaching the transducer's interior surfaces.

APPENDIC C/ POLAROID ULTRASONIC UNIT

POLAROID ULTRASONIC RANGING UNIT

Introduction

The purpose of this manual is to familiarize you with the Polaroid Ultrasonic Ranging Unit. It is intended to provide enough detail so that you can easily conduct tests and experiments with this device to determine its suitability to your needs.

This kit is intended for experimental use only.

The first section of this manual is a brief overview of the major components of the system and their function. The second section contains the information you will need to operate and interface with this device. In addition, typical waveforms, timing diagrams, schematics and characteristic graphs are included.

Section three describes the experimental demonstration board included in this kit. This board will enable you to immediately begin your evaluation of the ranging unit with a minimum of effort.

At the end of this manual, you will find technical specification sheets. We at Polaroid look forward to your continued interest in our ultrasonic products as well as the other Polaroid products included in this kit.

Please note that components other than the ultrasonic transducer are available for sale in limited quantities.

This kit comes complete with:

(1) 2-Polaroid Instrument-Grade Electrostatic Transducers
(2) 1-Polaroid Ultrasonic Circuit Board (modified)
(3) 1-Experimental Demonstration Board
(4) 1-Polaroid Circular Polarizer
(5) 2-Polaroid Polapulse Batteries
(6) 1-Polapulse Battery Holder
(7) Assorted Connectors and Wires

For additional information or technical assistance write:

Polaroid Corporation
Ultrasonic Ranging Marketing
1 Upland Road
Norwood, Massachusetts 02062

Or call toll free from the continental U.S.:

800-225-1618

In Massachusetts call collect: 617-547-5177

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I - GENERAL DESCRIPTION

Two primary components comprise the Polaroid Ultrasonic Ranging Unit; they are an acoustical transducer and ultrasonic circuit board (Figure 1).

Together these components are capable of detecting the presence and distance of objects within a range of approximately 0.9 feet to 35 feet. In operation, a pulse is transmitted toward a target and the resulting echo is detected. The elapsed time between initial transmission and echo detection can then be converted to distance with respect to the speed of sound. For a transmitted pulse to leave the transducer, strike a target two feet away, and to return to the transducer, requires an average time lapse of 3.55 milliseconds.

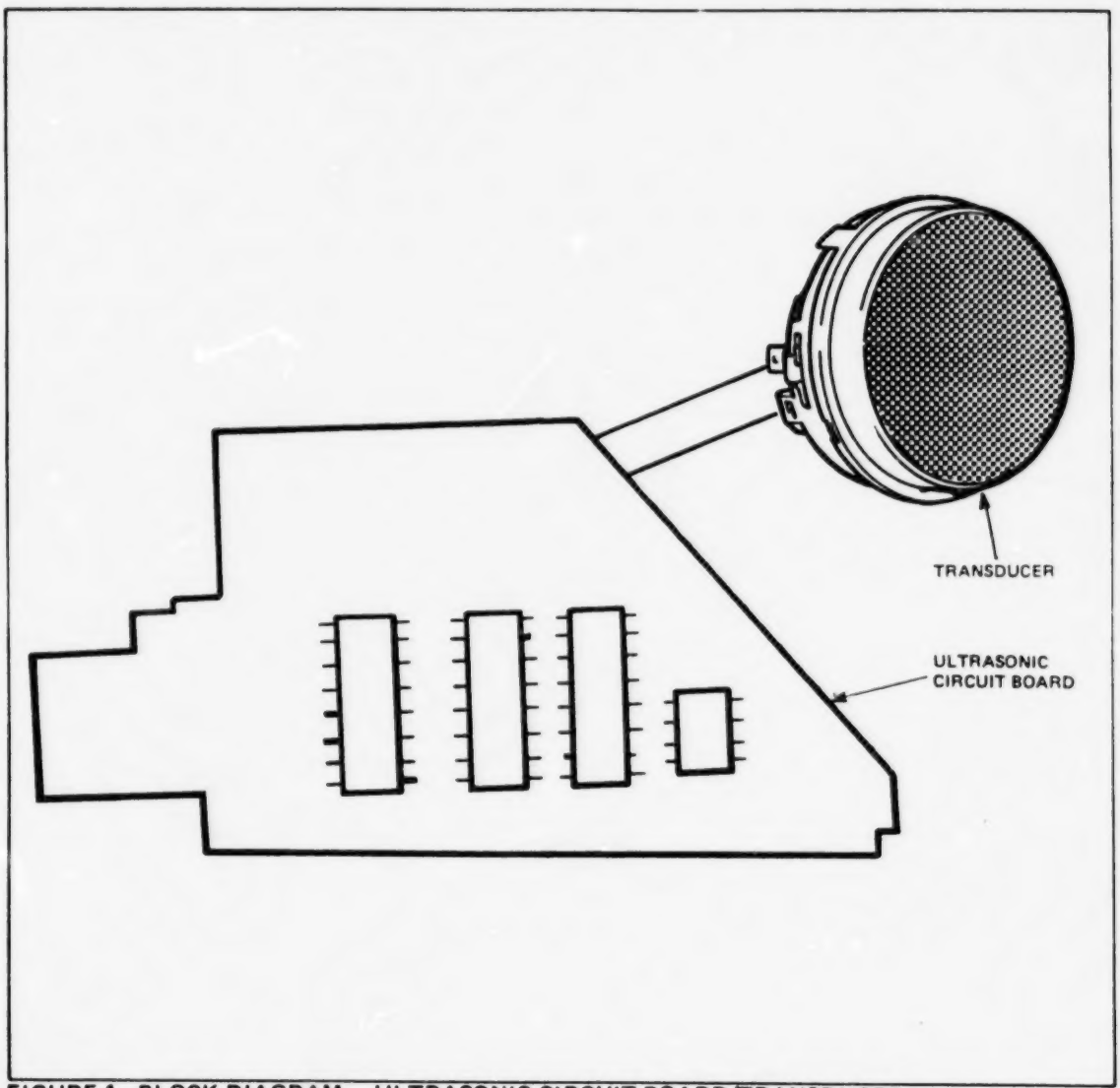


FIGURE 1. BLOCK DIAGRAM – ULTRASONIC CIRCUIT BOARD/TRANSDUCER

The principal component in this device is the transducer (Figure 2), which acts as both loudspeaker and microphone. It has been designed to transmit the outgoing signal and also to function as an electrostatic microphone in order to receive the reflected signal (the echo). Its diameter determines the acoustical lobe pattern, or acceptance angle, during the transmit and receive operation. A special, Polaroid manufactured foil is stretched over a grooved plate, forming the moving element which transforms electrical energy into sound waves and the returning echo back into electrical energy. The grooved, metallic backplate in contact with the foil forms a capacitor which, when charged, exerts an electrostatic force to the foil. The foil is pliable, capable of resisting harsh environments, and an excellent electrical conductor.

NOTE: Polaroid Corporation offers two grades of electrostatic transducers for sale; Instrument Grade and Commercial Grade. The Instrument Grade transducer is included in this kit to meet the performance demand of the ultrasonic circuit board to range between 0.9 feet and 35 feet. If your application is less demanding, or different from our technique of distance ranging, the Commercial Grade transducer may be more appropriate. Please be aware that the ultrasonic circuit board, as described in this manual, is not guaranteed to operate reliably with anything but Polaroid's Instrument Grade electrostatic transducer.

Under no circumstances should the user attempt to rebuild the transducer as this will change its acoustical characteristics.

WARNING: Be certain that the transducer is properly connected to the ultrasonic circuit board before applying power. Applying power to the board with the transducer disconnected may damage the board.

When the unit is activated, the transducer emits a sound pulse, then waits to receive the echo returning from whatever object the sound pulse has struck. The emitted pulse is a high-frequency, inaudible "chirp," lasting for one millisecond and consisting of fifty-six pulses at four carefully-chosen, ultrasonic frequencies; 60 kHz, 57 kHz, 53 kHz and 50 kHz. Occasionally, a single frequency could be cancelled because of certain target topographical characteristics, and no echo would be reflected. This device uses four frequencies to overcome that possibility.

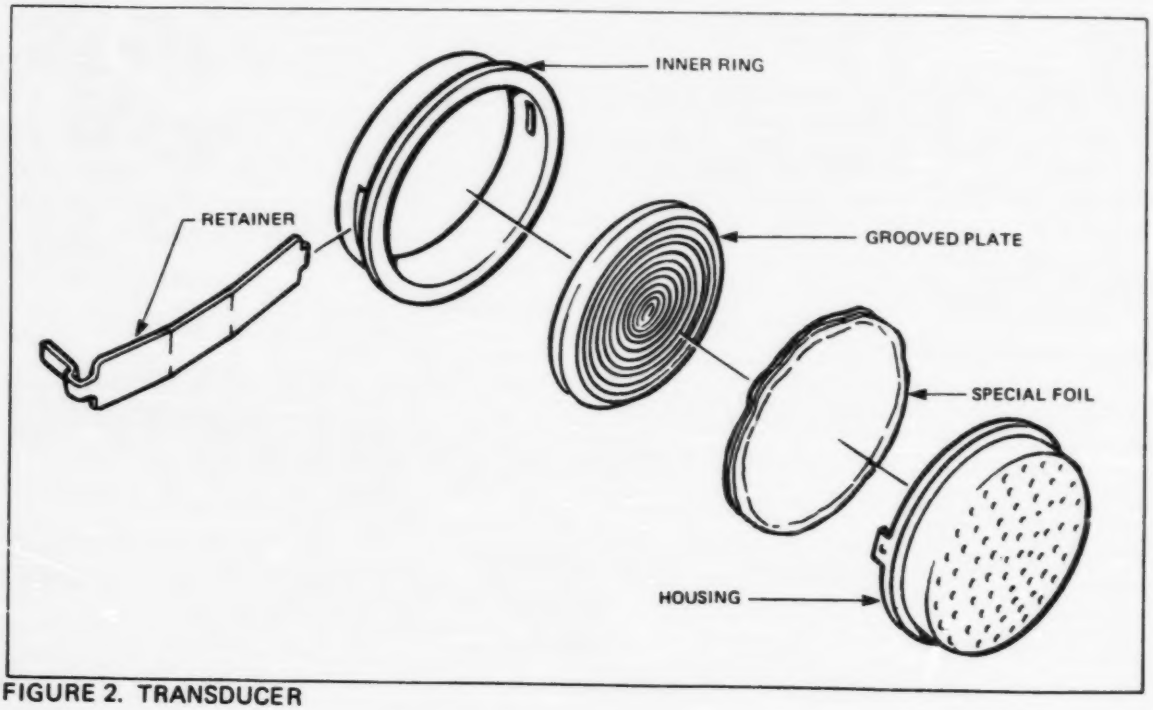


FIGURE 2. TRANSDUCER

The ultrasonic circuit board electronics (Figure 3) control the operating mode (transmit/receive) of the transducer. It is comprised of three major sections, which control transducer operation and allow the information gathered by it to be used as desired. Among the sections are: a digital circuit, an analog circuit and a power section.

NOTE: Although the Dual PNP section is present, it is not used in any of the circuits described in this book.

Powered by a 6 VDC supply, capable of 1 ms current surges of at least 2.5 AMPS, an appropriate drive circuit initiates the transmission of an ultrasonic pulse by the transducer (Figure 4). (Several drive circuits are described later in this book.)

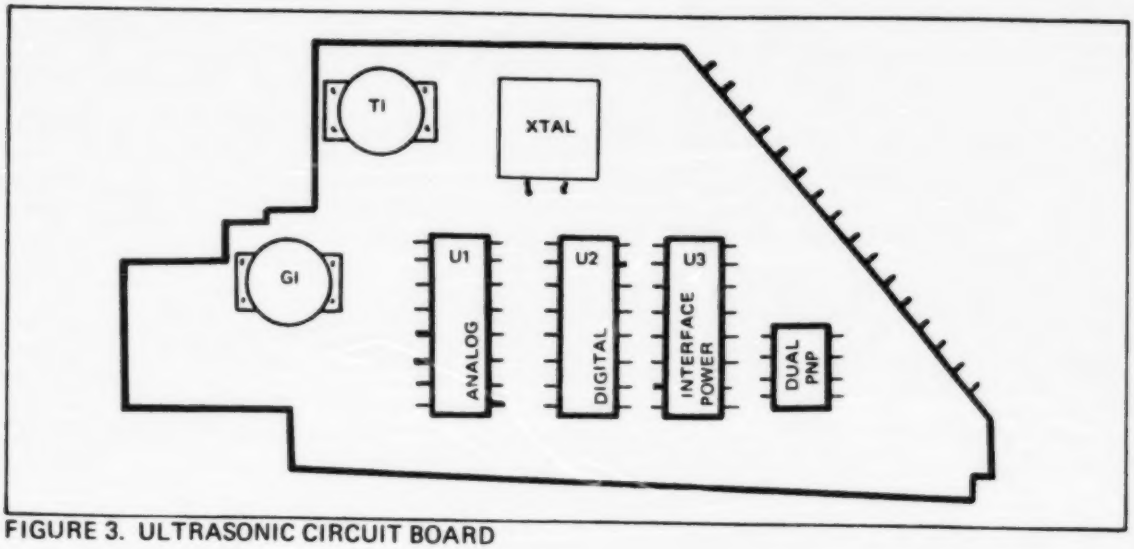


FIGURE 3. ULTRASONIC CIRCUIT BOARD

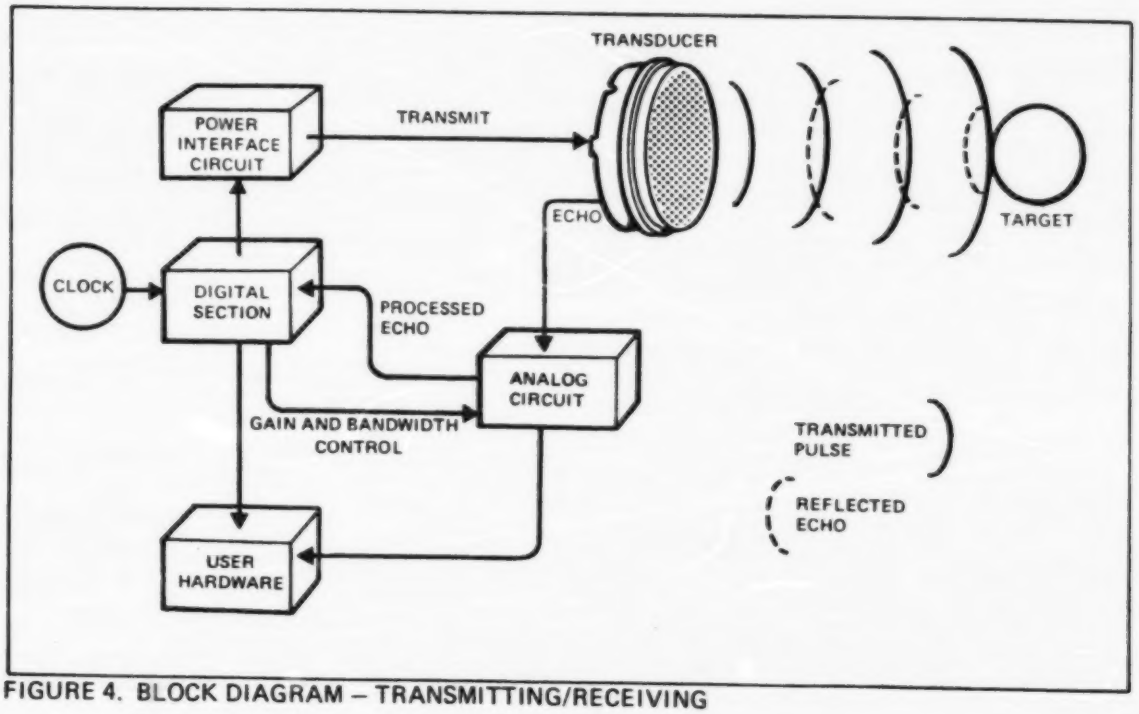


FIGURE 4. BLOCK DIAGRAM – TRANSMITTING/RECEIVING

A crystal-controlled clock in the digital circuit generates the ultrasonic frequencies that comprise the pulse transmitted by the transducer.

After generating the "chirp," the operating mode of the transducer changes, in effect, from loudspeaker to microphone to detect the returning echo. Upon receiving the echo, the transducer converts the sound energy to electrical energy, which is amplified by the analog circuit, then detected by the digital circuit to produce the echo received signal.

WARNING: A 300 volt signal is applied across the transducer each time a "chirp" is transmitted. Anyone contacting this signal during transmission will feel a noticeable, but harmless, shock.

Because of the reduction in return signal strength (echo) over longer distances (return signal power at 35 feet is almost a million times weaker than at 3 feet), a dual role is played by the amplifier within the analog circuit. In addition to processing the echo, the amplifier also performs the function of maintaining a tailored sensitivity over the entire operating range (distance covered) of the system. Lower amplification is needed for close echoes, while higher amplification is needed for distant echoes. The change in amplification is accomplished by increasing the gain and the Q of the amplifier in eight steps, out to 13.3 feet, and then by increasing just the gain of the amplifier, again in eight steps, beyond 13.3 feet. As you may see, a tailored sensitivity over the entire operating range is important and necessary.

NOTE: The overall gain can be adjusted with potentiometer R6 (24, Fig. 5). Excessive gain may cause a false receive indication just after transmit; insufficient gain may cause intermittent, far-field detection. These conditions, created by differences among Polaroid Instrument Grade Transducers, should be corrected by adjusting R6.

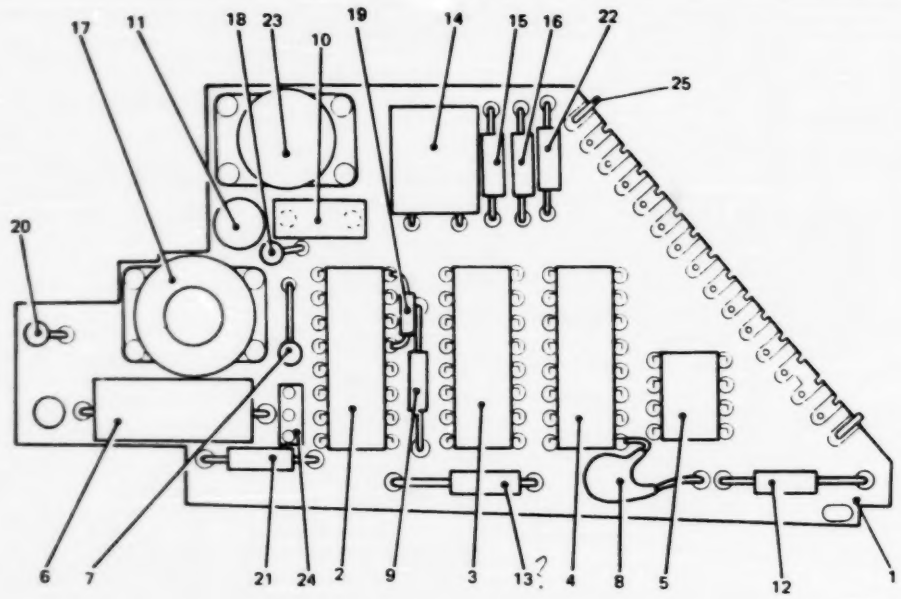
In our camera systems we maintain one strict rule concerning our ultrasonic modules. From time of transmit to receive, we inhibit all other high current electronic or electro-mechanical camera activity. This insures as noise-free an environment as possible. This is important because in the later high gain steps, the Ultrasonic Circuit Board is very susceptible to noise. The user should be aware of this when interfacing the Ultrasonic Circuit Board with other electronics.

With this brief description as a base, pertinent operating details will now be presented as an aid in using the system and in establishing and monitoring its performance.

II - USING THE POLAROID ULTRASONIC RANGING UNIT

Following are suggested circuits and circuit-board modifications that enable the Ranging Unit to be examined and used in various ways. Bear in mind that **these are only suggestions** to help you get started. There may be other ways to adapt this module to your needs; however, these circuits will allow immediate use of this device for your evaluation.

Figures 5 and 6 are component-layout and schematic diagrams respectively. Refer to these figures to familiarize yourself with the circuit boards.



ITEM	REF.	DESCRIPTION
1		PC BOARD
2	U1	ANALOG DIP
3	U2	DIGITAL DIP
4	U3	INTERFACE DIP
5	U4	DUAL (PNP) DIP
6	C1	CAPACITOR .01μf, 10V
7	C2	CAPACITOR .01μf, 50V
8	C3	CAPACITOR 1μf, 35V
9	C4	CAPACITOR .001μ, 10V
10	C5	CAPACITOR .0022μf, 400V
11	C6	OMITTED
12	C7	CAPACITOR .1μf, 50V
13	C8	CAPACITOR .01μf, 10V

ITEM	REF.	DESCRIPTION
14	XTAL	CRYSTAL
15	CR1	DIODE ZENER (IN990B)
16	CR2	DIODE ZENER (IN990B)
17	L1	TUNED CIRCUIT INDUCTOR
18	R1	RESISTOR ¼W (SEE NOTE 1)
19	C9	CAPACITOR .01μf, 50V
20	R3	RESISTOR (75 K, CF, ±5% ¼W)
21	R4	RESISTOR (75 K, CF, ±5% ¼W)
22	R5	RESISTOR (30 K, CF, ±5% ¼W)
23	T1	TRANSFORMER
24	R6	RESISTOR VARIABLE
25		PIN, MALE (SEE NOTE 2)

NOTE 1: RESISTOR VALUE SET AT FACTORY.
NOTE 2: FITS BERG 47217 CONNECTOR.

FIGURE 5. COMPONENT LAYOUT

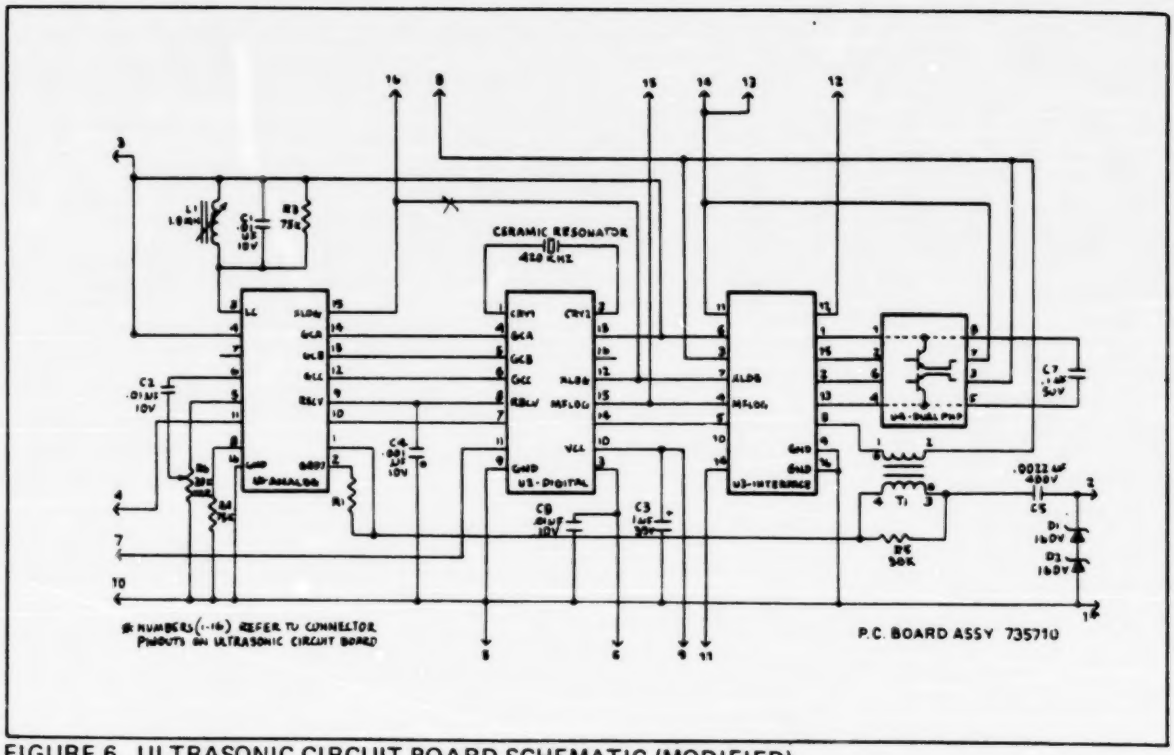


FIGURE 6. ULTRASONIC CIRCUIT BOARD SCHEMATIC (MODIFIED)

A. WAVEFORMS

The waveforms (Figure 7) presented here illustrate the pertinent timing relationships. These waveforms apply to a circuit board modified as shown in Figure 8.

1. Power (VSW)

Circuit power is obtained as shown in Figure 8. A 6 VDC 2.5 AMP power supply is required. Power for all circuits described in this manual can be obtained from the Polapulse Batteries provided in the kit. Simply insert a battery into the battery holder (Figure 9),and connect your chosen circuit to the appropriate terminals.

WARNING: Be certain that the transducer is properly connected to the ultrasonic circuit board before applying power. Applying power to the board with the transducer disconnected may damage the board.

A multiple drive logic signal, MDL, initiates a transmit/receive cycle by supplying the ultrasonic circuit board with the VSW signal (Figure 7). For proper operation, MDL should be high for 100 ms and low for a minimum of 100 ms.

NOTE: Production of drive signal MDL will be described in Part C of this section of this book. Timing relationships should not be established with respect to this signal, because the transmit signal (XLG, para. 2 below) does not start at a time that is precisely repeatable after the application of power.

Components in the VSW circuit, identified with an asterisk (*), comprise a speed-up circuit to allow rapid cycling. With the speed-up circuit, off-time can be as short as 40 ms. If rapid cycling is not desired, those components identified with an asterisk (*) can be omitted.

2. Transmission (XLG)

XLG (Figure 7) is the digital logic drive for the transmitted signal. It consists of eight cycles at 60 kHz, eight cycles at 57 kHz, sixteen cycles at 53 kHz and twenty-four cycles at 50 kHz for a total of fifty-six cycles and lasts for a period of about 1 millisecond. All timing relationships between transmitted signals and received echos are determined from the leading edge of this signal.

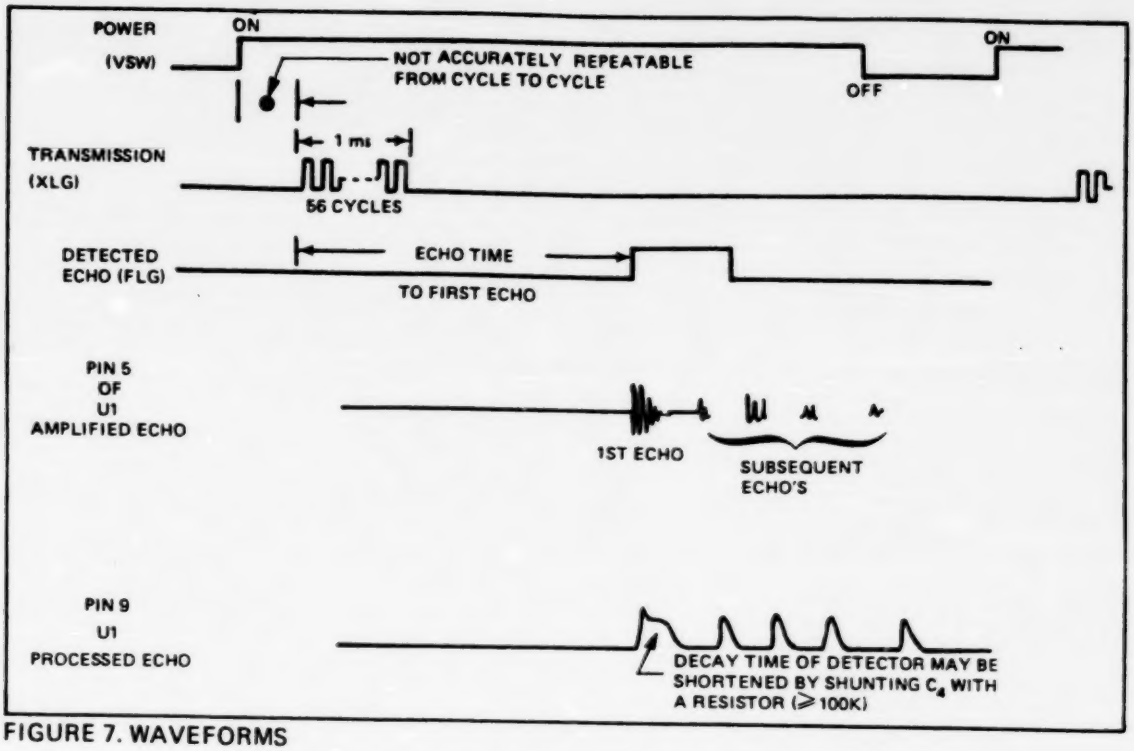


FIGURE 7. WAVEFORMS

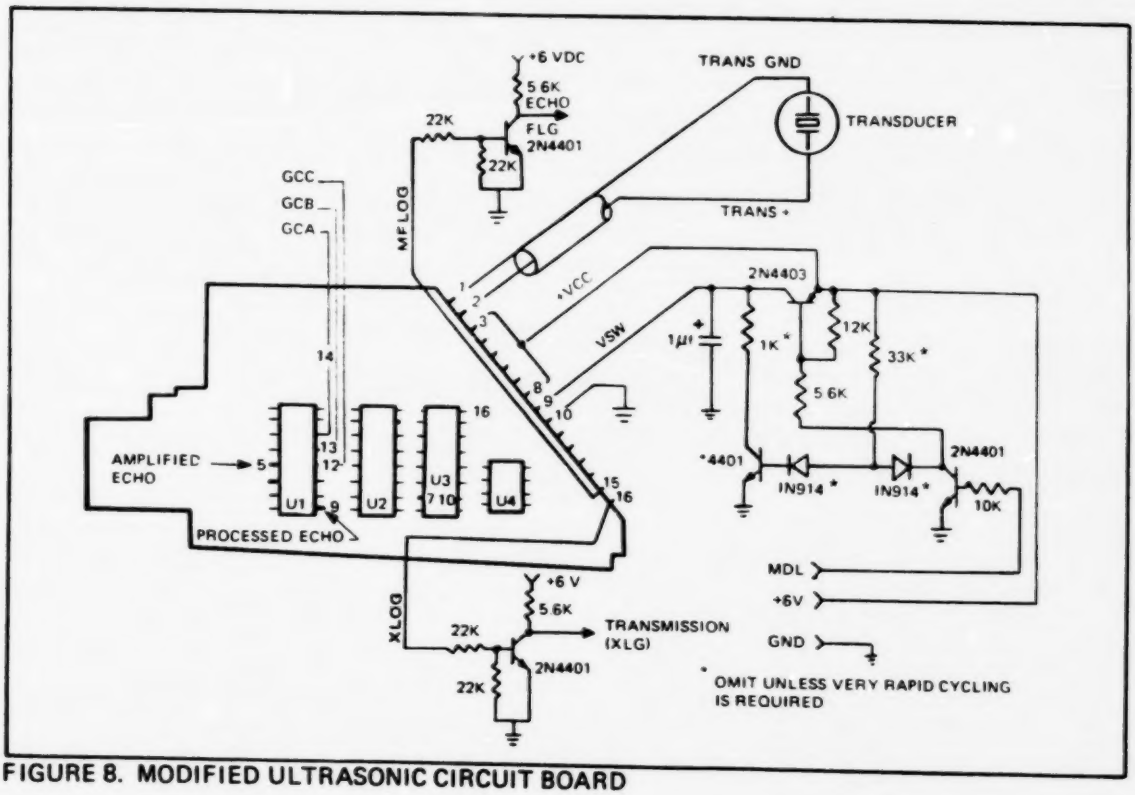


FIGURE 8. MODIFIED ULTRASONIC CIRCUIT BOARD

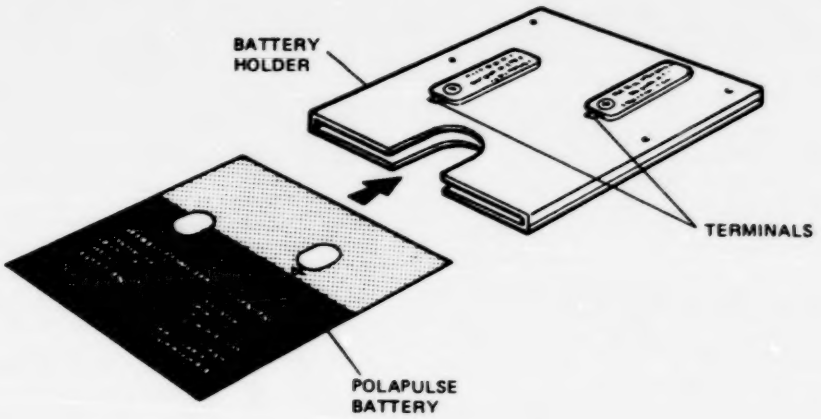


FIGURE 9. POLAPULSE BATTERY AND HOLDER

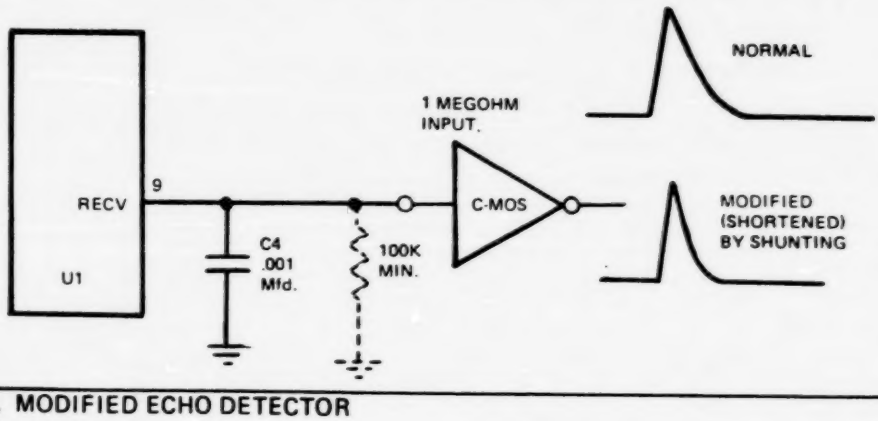


FIGURE 10. MODIFIED ECHO DETECTOR

The interface circuit for extracting this signal is shown at the bottom of Figure 8. The input signal for this circuit is obtained at terminal 16 of the ultrasonic circuit board.

3. Amplified Echo

The amplified echo (Figure 7) can be observed at pin 5 of U1 (Figure 8). This signal is useful for observing the reflected echos. Echos below detector threshold may also be viewed here. Normally this signal would not be extracted; however, this is the place to look when adjusting the gain of the module.

4. Processed Echo

The processed echo (Figure 7) can be observed at pin 9 of U1 as shown in Figure 8. The decay time of this signal may be shortened by shunting capacitor C4 with a resistor of at least 100k ohms. C-MOS circuits (Figure 10), or circuits of at least one megohm input impedance, provide a convenient way to extract this signal, if desired. This signal is useful if echos, other than the first echo, are of interest.

5. Detected Echo (FLG)

FLG (Figure 7) is the signal which indicates that the echo (the reflected transmission signal) has been received. It is obtained from terminal 15 of the ultrasonic circuit board. The interface circuit for extracting FLG is shown at the top of Figure 8, and is identical with that used for XLG.

B. GAIN CONTROLLING LOGIC

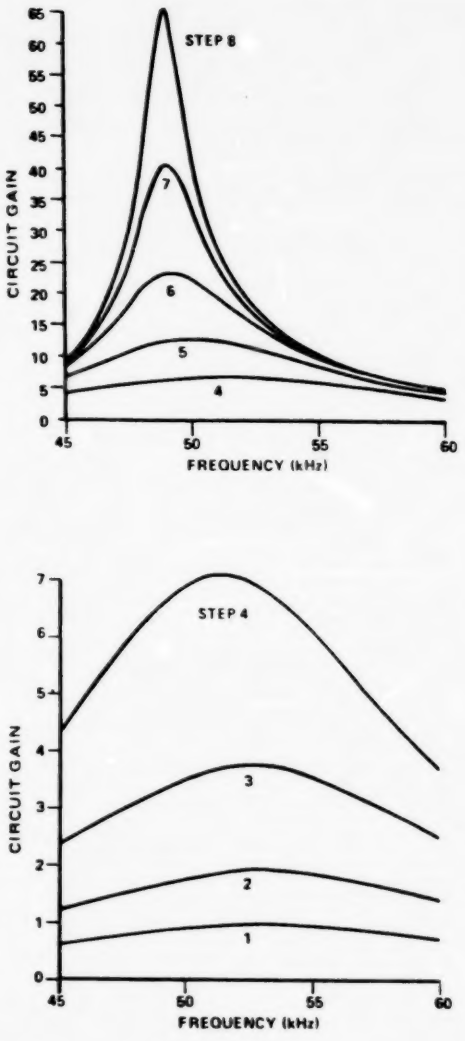
Three logic signals control the system gain and bandwidth as a function of time. The timing and performance relationships between the logic signals, gain and bandwidth are shown in Figure 12.

The gain controlling logic can be observed at the following points (Figure 8):

GCA at pin 14 of U1
GCB at pin 13 of U1
GCC at pin 12 of U1

Interface circuits, identical to those used for FLG and XLG, can also be used for these gain signals. Gain changes can be made by changing resistor R1 on the circuit board (Figure 5) and by adjusting potentiometer R6.

NOTE: The bandwidth changes continuously with time in eight steps, but is continuously narrow for the second eight steps and centered at about 50 kHz (see Figure 11).



*NOTE: Only the graphs of the first eight gain steps are included here for clarity. Steps 9-16 are identical to step 8 except that each successive step is increased in gain by 4 db.
These graphs are generated from theoretical information, not experimental data.

FIGURE 11. POLAROID ULTRASONIC RANGING UNIT GAIN VS. FREQUENCY*

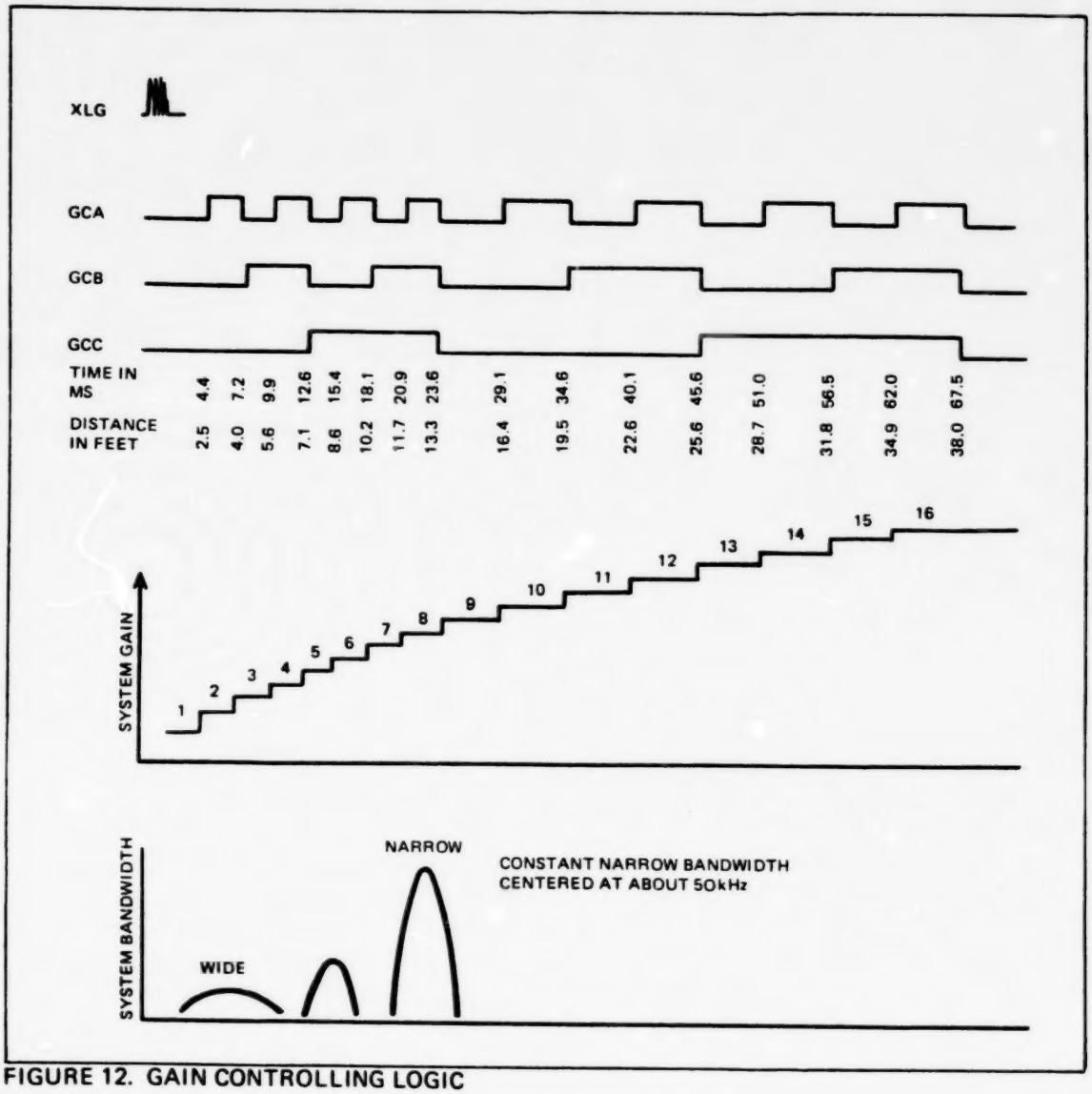


FIGURE 12. GAIN CONTROLLING LOGIC

C. SUGGESTED DRIVE CIRCUITS

As mentioned in part A.1. of this section, the production of drive signal MDL will be discussed here. Although there may be other methods for driving the ultrasonic unit, these circuit configurations have been tested and found to perform well while being simple to construct. In addition, they will enable you to quickly use and evaluate the ultrasonic unit.

The primary component in the following configurations are C-MOS devices (74C14 hex Schmitt triggers) which work quite well as drive circuits.

Figure 13 is a symmetrical drive, suitable for generating one-to-five repetitions per second (rps). Both pulse duration and off-time are approximately equal to $T \cong RC$.

Figure 14 is an asymmetrical drive, capable of providing up to 10 rps with long "on" symmetry. As above, pulse duration is approximately equal to $T_1 \cong R_1C$; however, off-time is equal to approximately:

$$T_2 \cong \frac{R_1R_2}{R_1+R_2} \times C.$$

Figure 15 is also an asymmetrical drive; however, it is designed to provide as little as 4 repetitions

per minute with long "off" symmetry. Pulse duration is approximately equal to:

$$T_1 \cong \frac{R_1 R_2}{R_1+R_2} \times C;$$

off time is approximately equal to $T_2 \cong R_1 C$.

Figure 16 is included here for its application value rather than as a general drive circuit. It is a method of cycling several systems in sequence repeatedly so that they do not interfere with each other.

This circuit is a digital system utilizing a symmetrical drive. (All components are identified on the drawing.) Very slow repetition rates can be achieved with this circuit, and it can be used to drive up to eight modules in sequential order.

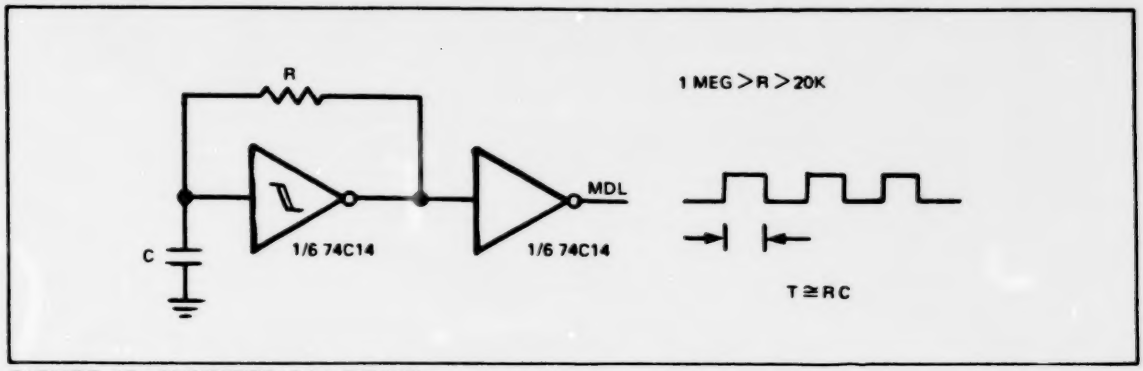


FIGURE 13. SYMMETRICAL DRIVE

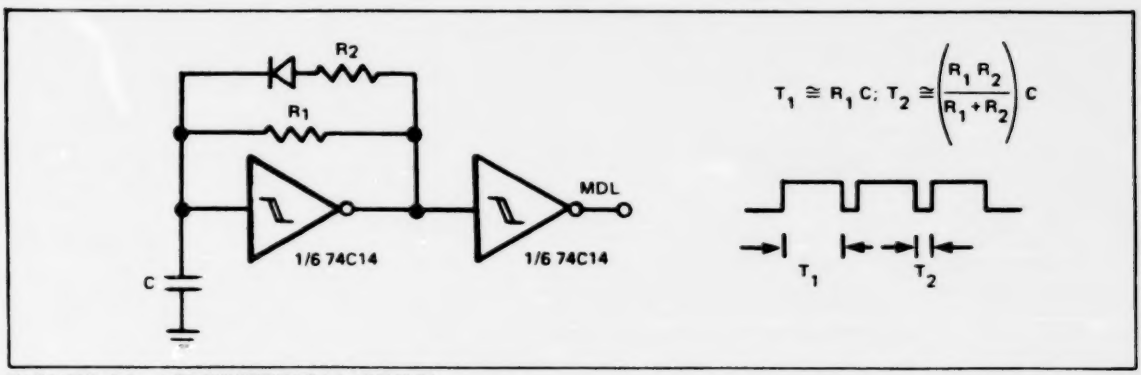


FIGURE 14. ASYMMETRICAL DRIVE

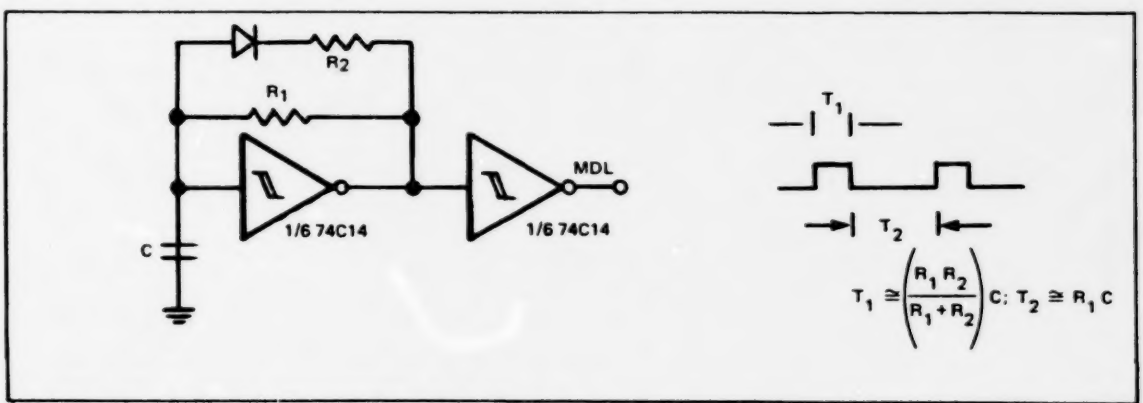


FIGURE 15. SLOW ASYMMETRICAL DRIVE

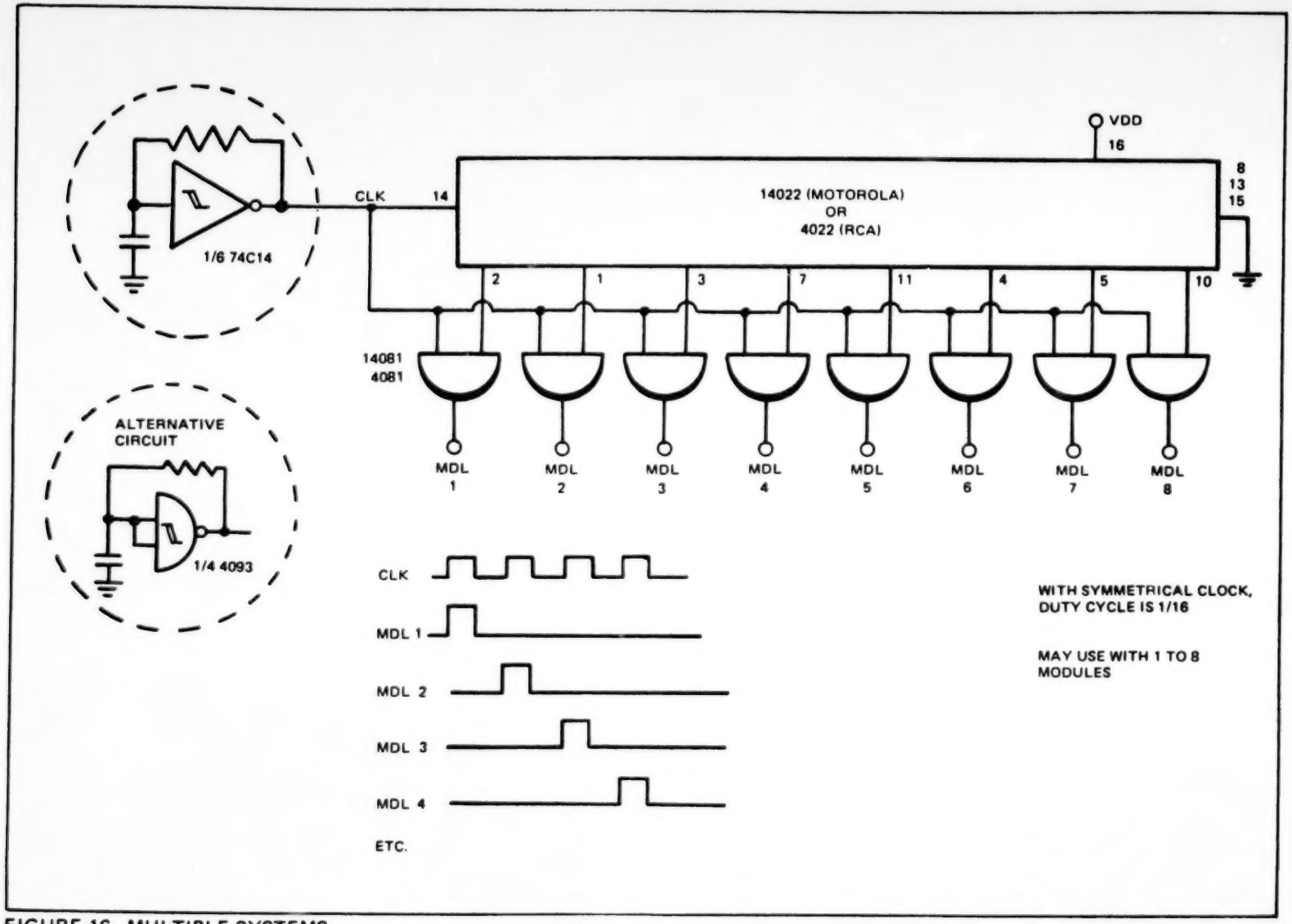


FIGURE 16. MULTIPLE SYSTEMS

Figure 17 is a fixed gain test circuit. It is a simple circuit that may be built from readily available parts. The circuit produces a single frequency transmit burst of 8, 16, 32 or 64 cycles and repeats at regular intervals of about 200 ms. It features adjustable blanking, a fixed gain amplifier, a detector and complementary, buffered, echo-detect outputs. The transmit frequency is adjustable by means of a potentiometer.

This circuit is intended as a starting point in arriving at a system design where the sophistication of the ultrasonic circuit board is not needed.

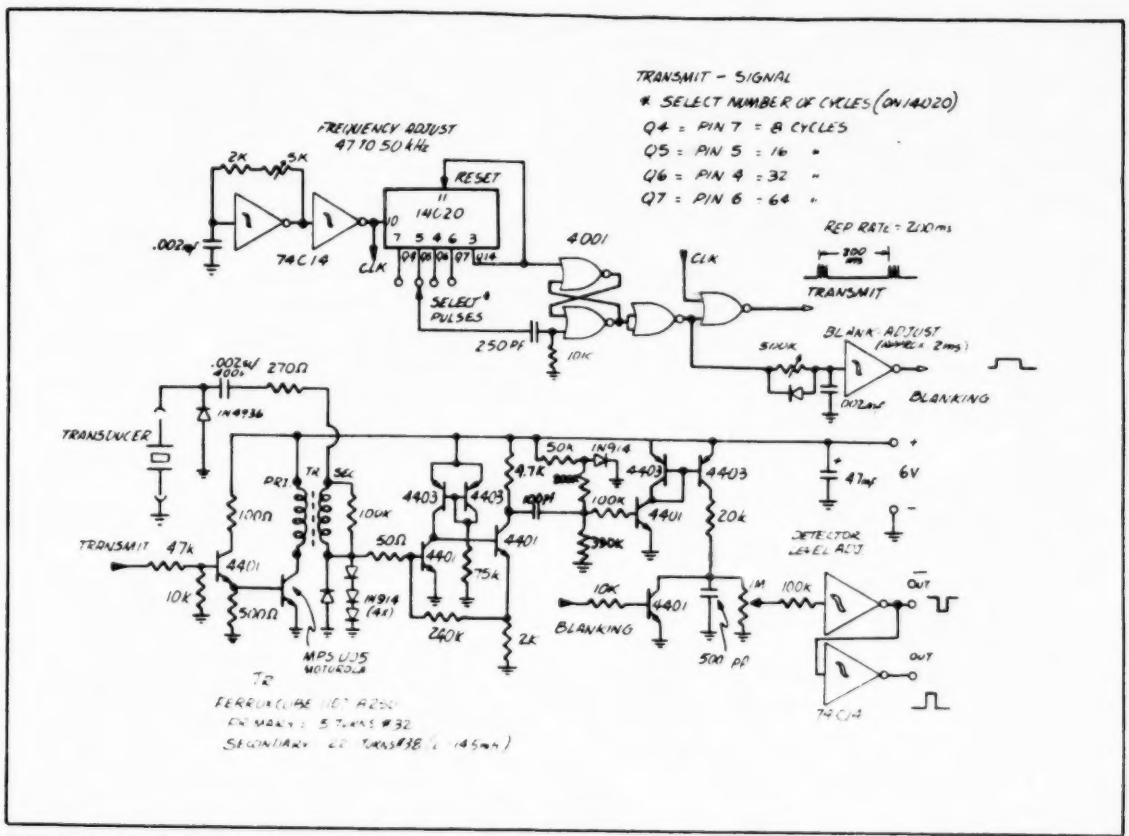
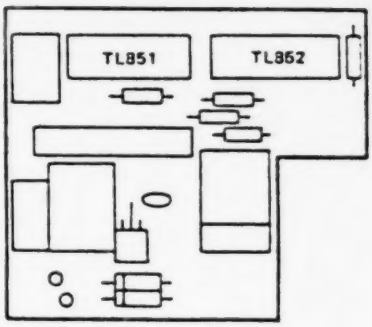


FIGURE 17. FIXED-GAIN TESTER CIRCUIT

APPENDIX D/ TEXAS INSTRUMENTS SONAR UNIT

- Accurate Sonar Ranging from 6 Inches to 35 Feet
- Drives 50-kHz Electrostatic Transducer with No Additional Interface
- Operates from Single Supply
- Accurate Clock Output Provided for External Use
- Selective Echo Exclusion
- TTL-Compatible
- Multiple Measurement Capability
- Uses TL851 and TL852 Sonar Ranging Integrated Circuits



description

The SN28827 is an economical sonar ranging module that can drive a 50-kilohertz, 300-volt electrostatic transducer with no additional interface. This module, with a simple interface, is able to measure distances ranging from 6 inches to 35 feet. The typical absolute accuracy is ±2% at one foot or greater.

This module has an external blanking input that allows selective echo exclusion for operation in a multiple-echo mode. The module is able to differentiate echos from objects that are only three inches apart. The digitally controlled-gain, variable-bandwidth amplifier minimizes noise and side-lobe detection in sonar applications.

The module has an accurate ceramic-resonator-controlled 420-kilohertz time-base generator. An output based on the 420-kilohertz time base is provided for external use. The sonar transmit output is 16 cycles at a frequency of 49.4 kilohertz.

The SN28827 operates over a supply voltage range of from 4.5 volts to 6.8 volts and is characterized for operation from 0°C to 40°C.

absolute maximum ratings

Voltage from any pin to ground (see Note 1)	7 V
Voltage from any pin except XDCR to V_{CC} (see Note 1)	−7 V to 0.5 V
Operating free-air temperature range	0°C to 40°C
Storage temperature range	−40°C to 85°C

NOTE 1: The XDCR pin may be driven from −1 volt to 300 volts typical with respect to ground.

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recommended operating conditions

		MIN	MAX	UNIT
Supply voltage, V_{CC}		4.5	6.8	V
High-level input voltage, V_{IH}	BLNK, BINH, INIT	2.1		V
Low-level input voltage, V_{IL}	BLNK, BINH, INIT		0.6	V
ECHO and OSC output voltage			6.8	V
Delay time, power up to INIT high		5		ms
Recycle period		80		ms
Operating free-air temperature, T_A		0	40	°C

electrical characteristics over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
Input current	BLNK, BINH, INIT	V_I = 2.1 V			1	mA
High-level output current, I_{OH}	ECHO, OSC	V_{OH} = 5.5 V			100	µA
Low-level output voltage, V_{OL}	ECHO, OSC	I_{OL} = 1.6 mA			0.4	V
Transducer bias voltage		T_A = 25°C		150		V
Transducer output voltage (peak-to-peak)		T_A = 25°C		300		V
Number of cycles for XDCR output to reach 300 V		C = 500 pF			7	
Internal blanking interval				2.38†		ms
Frequency during 16-pulse transmit period	OSC output			49.4†		kHz
	XMIT output			49.4†		
Frequency after 16-pulse transmit period	OSC output			93.3†		kHz
	XMIT output			0		
Supply current, I_{CC}	During transmit period				2000	mA
	After transmit period				100	

†These typical values apply for a 420-kHz ceramic resonator.

operation with Polaroid electrostatic transducer

There are two basic modes of operation for the SN28827 Sonar ranging module: single-echo mode and multiple-echo mode. The application of power (V_{CC}), the activation of the Initiate (INIT) input, and the resulting transmit output, and the use of the Blanking Inhibit (BINH) input are basically the same for either mode of operation. After applying power (V_{CC}), a minimum of 5 milliseconds must elapse before the INIT input can be taken high. During this time, all internal circuitry is reset and the internal oscillator stabilizes. When INIT is taken high, drive to the Transducer XDCR output occurs. Sixteen pulses at 49.4 kilohertz with 300-volt amplitude will excite the transducer as transmission occurs. At the end of the 16 transmit pulses, a dc bias of 150 volts will remain on the transducer as recommended for optimum operation by the transducer manufacturer.

In order to eliminate ringing of the transducer from being detected as a return signal, the Receive (REC) input of the ranging control IC is inhibited by internal blanking for 2.38 milliseconds after the initiate signal. If a reduced blanking time is desired, then the BINH input can be taken high to end the blanking of the Receive input anytime prior to internal blanking. This may be desired to detect objects closer than 1.33 feet corresponding to 2.38 milliseconds and may be done if transducer damping is sufficient that ringing is not detected as a return signal.

In the single-echo mode of operation (Figure 1), all that must be done next is to wait for the return of the transmitted signal, traveling at approximately 0.9 milliseconds per foot out and back. The returning signal is amplified and appears as a high-logic-level echo output. The time between INIT going high and the Echo (ECHO) output going high is proportional to the distance of the target from the transducer. If desired, the cycle can now be repeated by returning INIT to a low-logic level and then taking it high when the next transmission is desired.

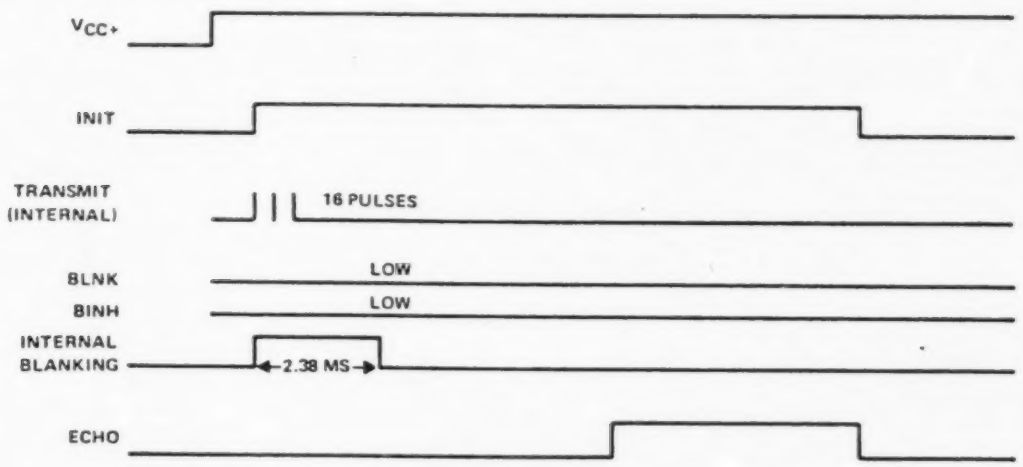


FIGURE 1–EXAMPLE OF A SINGLE-ECHO-MODE CYCLE WITHOUT BLANKING INPUT

If there is more than one target and multiple echos are to be detected from a single transmission, then the cycle is slightly different (Figure 2). After receiving the first return signal, which causes the ECHO output to go high, the Blanking (BLNK) input must be taken high then back low to reset the ECHO output for the next return signal. The blanking signal must be at least 0.44 milliseconds in duration to account for all 16 returning pulses from the first target and allow for internal delay times. This corresponds to the two targets being 3 inches apart.

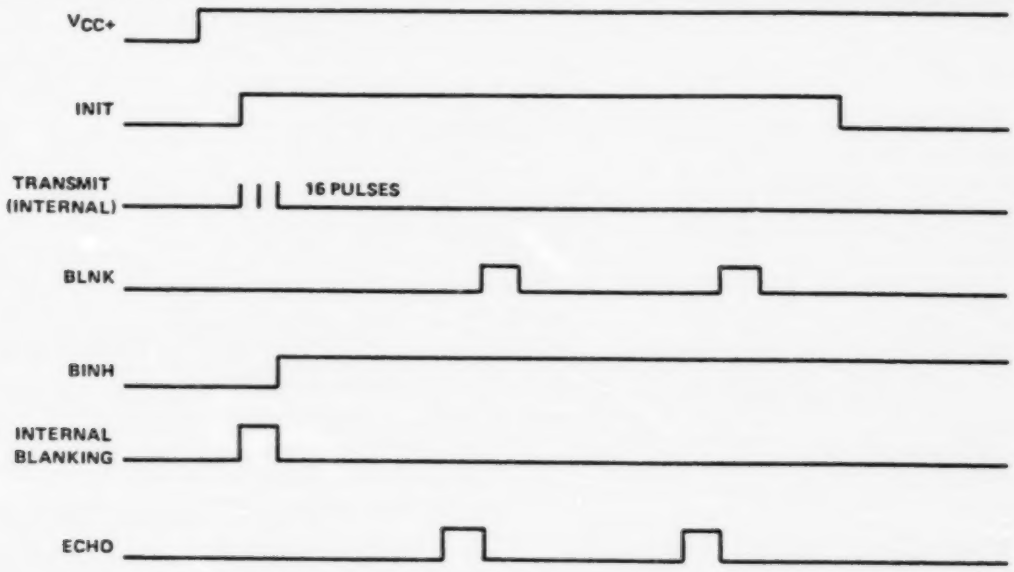


FIGURE 2–EXAMPLE OF A MULTIPLE-ECHO-MODE CYCLE WITH BLANKING INPUT

During a cycle starting with INIT going high, the receiver amplifier gain is incremented higher at discrete times (Figure 3) since the transmitted signal is attenuated with distance. At approximately 38 milliseconds, the maximum gain is attained. For this reason, sufficient gain may not be available for objects greater than

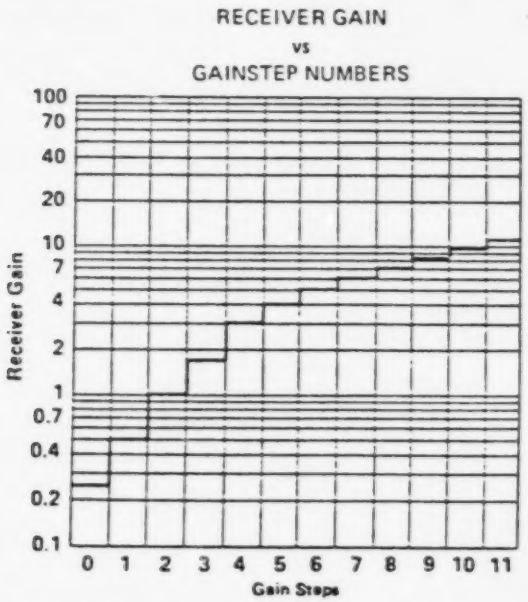


FIGURE 3

35 feet away. Although gain can be increased by varying R1 (Figure 4), there is a limit to which the gain can be increased for reliable module operation. This will vary from application to application. The modules are "kitted" prior to their final test during manufacture. This is necessary because the desired gain distribution is much narrower than the module gain distribution if all were kitted with one value resistor. As kitted, these modules will perform satisfactorily in most applications. As a rule of thumb, the gain can be increased by up to a factor of 4, if required, by increasing R1 correspondingly. Gain is directly proportional to R1.

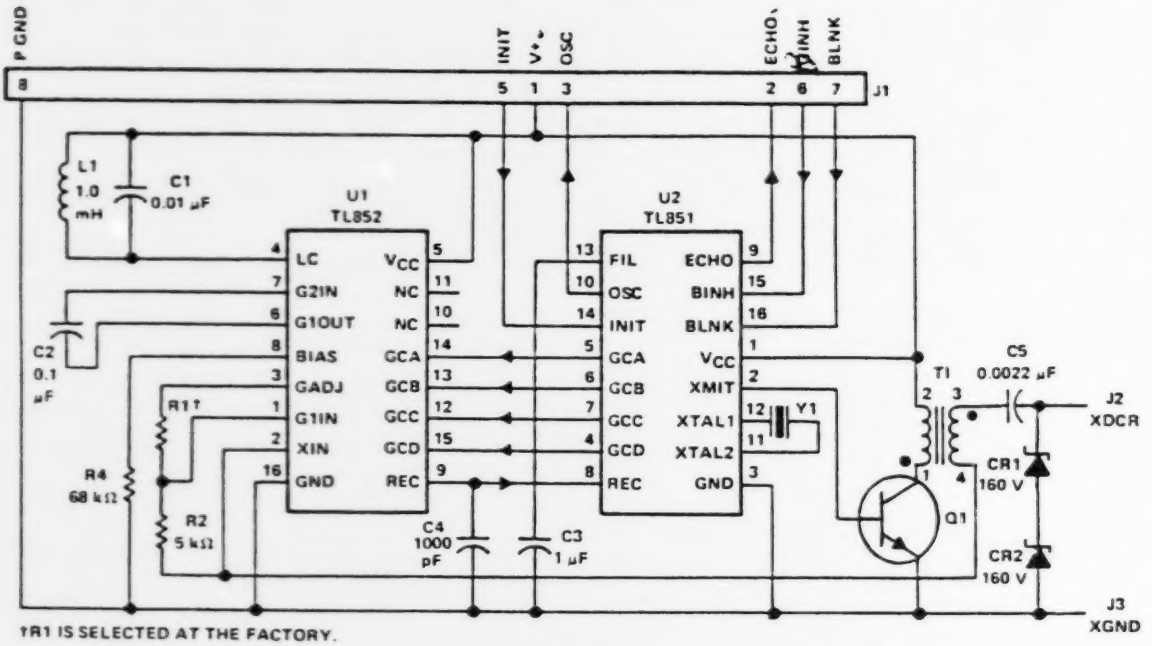
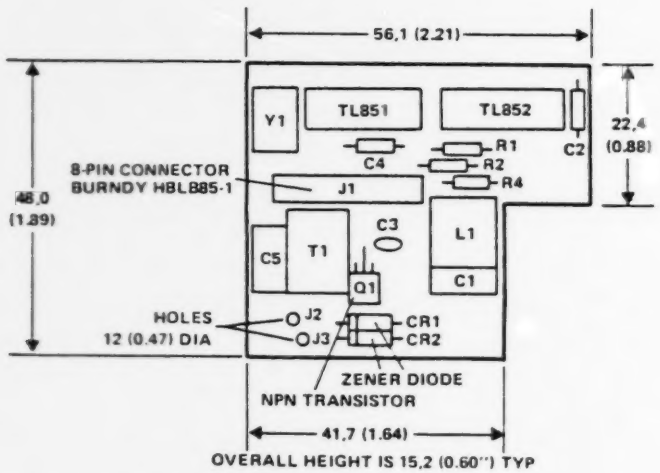


FIGURE 4–SCHEMATIC



NOTE: All dimensions are in millimeters and parenthetically in inches.

FIGURE 5 – COMPONENT LAYOUT AND DIMENSIONS OF MODULE